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PROPAGATION MODEL (0.1 to 20 GHz) EXTENSIONS FOR 1977 COMPUTER PROGRAMS

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U.S. DEPARTMENT OF COMMERCE
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16. Abstract

This report describes methods used in the 1977 extensions of the propagation model incorporated into computer programs for propagation and interference analysis (0.1 to 20 GHz). These extensions to the 1973 Model allow the programs to be used for a wider variety of problems such as those involving air/air or air/satellite propagation. Method descriptions are confined to mathematical formulations for modifications to the 1973 Model, and do not include program listings or flow charts. A detailed description of the 1973 Model, including program listings, is provided in DOT Report FAA-RD-73-103. Capabilities of the 1977 computer programs are mentioned, but not discussed in detail. These capabilities are covered in DOT Report FAA-RD-77-60 which is an APPLICATIONS GUIDE for the programs.

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ENGLISH/METRIC CONVERSION FACTORS

LENGTH

From \ To	Cm	m	Km	in	ft	s mi	n mi
Cm	1	0.1	1×10^{-5}	0.3937	0.0328	6.21×10^{-6}	5.39×10^{-6}
m	100	1	0.001	39.37	3.281	0.0006	0.0005
Km	100,000	1000	1	39370	3281	0.6214	0.5395
in	2.540	0.0254	2.54×10^{-5}	1	0.0833	1.58×10^{-5}	1.37×10^{-5}
ft	30.48	0.3048	3.05×10^{-4}	12	1	1.89×10^{-4}	1.64×10^{-4}
S mi	160,900	1609	1.609	63360	5280	1	0.8688
n mi	185,200	1852	1.852	72930	6076	1.151	1

AREA

From \ To	Cm^2	M^2	Km^2	in^2	ft^2	$S\ mi^2$	$n\ mi^2$
Cm^2	1	0.0001	1×10^{-10}	0.1550	0.0011	3.86×10^{-11}	5.11×10^{-11}
m^2	10,000	1	1×10^{-6}	1550	10.76	3.86×10^{-7}	5.11×10^{-7}
Km^2	1×10^{10}	1×10^{6}	1	1.55×10^{9}	1.08×10^{7}	0.3861	0.2914
in^2	6.452	0.0006	6.45×10^{-10}	1	0.0069	2.49×10^{-10}	1.88×10^{-10}
ft^2	929.0	0.0929	9.29×10^{-3}	144	1	3.59×10^{-8}	2.71×10^{-8}
$S\ mi^2$	2.59×10^{10}	2.59×10^{6}	2.590	4.01×10^{9}	2.79×10^{7}	1	0.7548
$n\ mi^2$	3.43×10^{10}	3.43×10^{6}	3.432	5.31×10^{9}	3.70×10^{7}	1.325	1

VOLUME

From \ To	Cm^3	Liter	m^3	in^3	ft^3	yd^3	fl oz	fl pt	fl qt	gal
Cm^2	1	0.001	1×10^{-6}	0.0610	3.53×10^{-5}	1.31×10^{-6}	0.0338	0.0021	0.0010	0.0002
liter	1000	1	0.001	61.02	0.0353	0.0013	33.81	2.113	1.057	0.2642
m^2	1×10^{6}	1000	1	61,000	35.31	1.308	33,800	2113	1057	264.2
in^3	16.39	0.0163	1.64×10^{-5}	1	0.0006	2.14×10^{-5}	0.5541	0.0346	2113	0.0043
ft^3	28,300	28.32	0.0283	1728	1	0.0370	957.5	59.84	0.0173	7.481
yd^3	765,000	764.5	0.7646	46700	27	1	25900	1616	807.9	202.0
fl oz	29.57	0.2957	2.96×10^{-5}	1.805	0.0010	3.87×10^{-5}	1	0.0625	0.0312	0.0078
fl pt	473.2	0.4732	0.0005	28.88	0.0167	0.0006	16	1	0.5000	0.1250
fl qt	948.4	0.9463	0.0009	57.75	0.0334	0.0012	32	2	1	0.2500
gal	3785	3.785	0.0038	231.0	0.1337	0.0050	128	8	4	1

MASS

From \ To	g	Kg	oz	lb	ton
g	1	0.001	0.0353	0.0022	1.10×10^{-6}
Kg	1000	1	35.27	2.205	0.0011
oz	28.35	0.0283	1	0.0625	3.12×10^{-5}
lb	453.6	0.4536	16	1	0.0005
ton	907,000	907.2	32,000	2000	1

TEMPERATURE

°F	=	5/9 (°C - 32)
°C	=	9/5 (°F) + 32

FEDERAL AVIATION ADMINISTRATION
SYSTEMS RESEARCH AND DEVELOPMENT SERVICE
SPECTRUM MANAGEMENT STAFF

Statement of Mission

The mission of the Spectrum Management Staff is to assist the Department of State, National Telecommunications and Information Administration, and the Federal Communications Commission in assuring the FAA's and the nation's aviation interests with sufficient protected electromagnetic telecommunications resources throughout the world to provide for the safe conduct of aeronautical flight by fostering effective and efficient use of a natural resource--the electromagnetic radio frequency spectrum.

This object is achieved through the following services:

- Planning and defending the acquisition and retention of sufficient radio frequency spectrum to support the aeronautical interests of the nation, at home and abroad, and spectrum standardization for the world's aviation community.

- Providing research, analysis, engineering, and evaluation in the development of spectrum related policy, planning, standards, criteria, measurement equipment, and measurement techniques.

- Conducting electromagnetic compatibility analyses to determine intra/inter-system viability and design parameters, to assure certification of adequate spectrum to support system operational use and projected growth patterns, to defend aeronautical services spectrum from encroachment by others, and to provide for the efficient use of the aeronautical spectrum.

- Developing automated frequency selection computer programs/routines to provide frequency planning, frequency assignment, and spectrum analysis capabilities in the spectrum supporting the National Airspace System.

- Providing spectrum management consultation, assistance, and guidance to all aviation interest, users, and providers of equipment and services, both national and international.

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G. D. GIERHART and M. E. JOHNSON[1]

1. INTRODUCTION

Assignments for aeronautical radio in the radio frequency spectrum must be made so as to provide reliable services for an increasing air traffic density [19][2]. Potential interference between facilities operating on the same or on adjacent channels must be considered in expanding present services to meet future demands. Service quality depends on many factors, including the desired-to-undesired signal ratio at the receiver. This ratio varies with receiver location and time even when other parameters, such as antenna gain and radiated powers, are fixed.

In 1973, an air/ground propagation model developed at the Department of Commerce Boulder Laboratories (DOC-BL) by the Institute for Telecommunication Sciences (ITS) for the Federal Aviation Administration (FAA) was documented in detail. This IF-73 (ITS-FAA-1973) propagation model has evolved into the IF-77 model, which is applicable to air/air, air/ground, air/satellite, ground/ground, and ground/satellite paths. The IF-77 has been incorporated into 10 computer programs that are useful in estimating the service coverage of radio systems operating in the frequency band from 0.1 to 20 GHz. These programs may be used to obtain a wide variety of computer-generated microfilm plots. A plotting capability summary is provided in table 1, and program input parameters are summarized in tables 2 through 4. These tables were

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[1]The authors are with the Institute for Telecommunication Sciences, National Telecommunications and Information Administration, U. S. Department of Commerce, Boulder, Colorado 80303.

[2]References are listed alphabetically by author at the end of the report so that reference numbers do not appear sequentially in the text.

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Table 1. Plotting Capability Guide [21, table 1]

Capability	Figure(s)*	Program	Remarks
Lobing**	6	LOBING	Transmission loss versus path distance.
Reflection coefficient**	7	LOBING	Effective specular reflection coefficient versus path distance.
Path length difference**	8	LOBING	Difference in reflected and direct ray lengths versus path distance.
Time lag**	9	LOBING	Same as above with path length difference expressed as time delay.
Lobing frequency-D**	10	LOBING	Normalized distance lobing frequency versus path distance.
Lobing frequency-H**	11	LOBING	Normalized height lobing frequency versus path distance.
Reflection point**	12	LOBING	Distance to reflection point versus path distance.
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Power available curves	21	ATLAS	Power available curves versus distance are provided for several aircraft altitudes with a selected time availability, and a fixed lower antenna height.
Power density curves	22	ATLAS	Similar to above, but with power density as ordinate.
Transmission loss curves	23	ATLAS	Similar to above, but with transmission loss as ordinate.
Power available volume	24	HIPOD	Fixed power available contours in the altitude versus distance plane for time availabilities of 5, 50, and 95 percent.
Power density volume	25	HIPOD	Similar to above, but with fixed power density contours.
Transmission loss volume	26	HIPOD	Similar to above, but with fixed transmission loss contours.
EIRP contours	27-29	APODS	Contours for several EIRP levels needed to meet a particular power density requirement are shown in the altitude versus distance plane for a single time availability.
Power available contours	30	APODS	Similar to above, but with power available contours for a single EIRP.
Power density contours	31	APODS	Similar to above, but with power density contours.
Transmission loss contours	32	APODS	Similar to above, but with transmission loss contours.
Signal ratio-S	33	ATADU	Desired-to-undesired, D/U, signal ratio versus station separation for a fixed desired facility-to-receiver distance, and time availabilities of 5, 50, and 95 percent.

Table 1. Plotting Capability Guide (con't)

Capability	Figure(s)*	Program	Remarks
Signal ratio-DD	34	DUDD	Similar to above, but abscissa is desired facility-to-receiver distance and the station separation is fixed.
Orientation	35	TWIRL	Undesired station antenna orientation with respect to the desired to undesired station line versus required facility separation curves are plotted for several desired station antenna orientations. These curves show the maximum separation required to obtain a specified D/U signal ratio value at several aircraft locations (i.e., protection points).
Service volume	36-37	SRVLUM	Fixed D/U contours are shown in the altitude versus distance plane for a fixed station separation and time availabilities of 5, 50, and 95 percent.
Signal ratio contours	38-39	DURATA	Contours for several D/U values are shown in the altitude versus distance plane for a fixed station separation and time availability.

* Additional discussion, by capability, is provided in APPLICATIONS GUIDE [21, sec. 3.2].
** Applicable only to the line-of-sight region for spherical earth geometry. Variability with time and horizon effects are neglected and the counterpoise option is not available. The phase change associated with surface reflection in the lobing region is taken as 0 or 180° to avoid missing lobe nulls.

taken from an APPLICATIONS GUIDE [21, tables 1, 2, 3, and 4] where the capabilities and input requirements are discussed in detail. The figure numbers in table 1 refer to sample capability graphs contained in the APPLICATIONS GUIDE. Hence, the APPLICATIONS GUIDE contains one or more sample graphs per capability. Even though an idea of the capabilities available and the input requirements can be obtained from these tables, anyone seriously considering using the capabilities should obtain and read a copy of the APPLICATIONS GUIDE [21].

This report covers extensions that were made to IF-73 in the process of developing the 1977 capabilities of table 1. These extensions allow the program to be used for a wider variety of problems such as those involving air/air or air/satellite propagation. A brief description of the propagation model provided in section 2 is followed by detailed discussions of specific model extensions. Minor changes made to IF-73 and errata for the 1973 report [17] are covered in Appendix A.

Except where otherwise indicated, all equations provided here are dimensionally consistent; e.g., all lengths in a particular equation are expressed in the same units. Calculations are made in the computer programs with all lengths expressed in kilometers. Braces are used around parameter dimensions when particular units are called for or when a potential dimension difficulty exists. A list of symbols is provided in Appendix B.

2. PROPAGATION MODEL

The IF-77 propagation model is applicable to air/ground, air/air, ground/satellite, and air/satellite paths. It can also be used for ground/ground paths that are line-of-sight or smooth earth. Model applications are restricted to telecommunication links operating at radio frequencies from about 0.1 to 20 GHz with antenna heights greater than 1.5 ft (0.5 m). In addition, radio-horizon elevations must be less than the elevation of the higher antenna. The radio horizon for the higher antenna is

Table 2. Parameter Specification, General [21, table 2]

Parameter	Range	Value
PRIMARY PARAMETERS, SPECIFICATION REQUIRED		
Aircraft (or higher) antenna height above mean sea level (msl)	≥ Facility horizon height	______ ft, m, km, n mi, s mi,
Facility (or lower) antenna height above facility site surface (fss)	> 1.5 ft (0.5 m) above fss	______ ft, m
Frequency	0.1 to 20 GHz	______ MHz
SECONDARY PARAMETERS, SPECIFICATION OPTION	Specified, Computed, or Assumed	
Aircraft antenna type options	Isotropic*, or as specified	
Beam width, half-power	0.1 to 45°	______ deg
Polarization options	None, identical with facility	
Tilt, main beam above horizontal	-90° to 90°	______ deg
Tracking options	Directional* or tracking	
Effective reflection surface elevation above msl	At fss* or specified value above msl	______ ft, m
Equivalent isotropically radiated power	0.0 dBW* or specified	______ dBW
Facility antenna type options	Isotropic* or as specified	
Beam width, half-power	0.1 to 45°	______ deg
Counterpoise diameter	0° to 500 ft (152 m)	______ ft, m
Height above fss	0* to 500 ft (152 m) Below facility antenna by at least 3 ft (1 m) but no more than 2000 ft (610 m)	______ ft, m
Surface options	Poor, average, or good ground, or fresh or sea water, concrete, or metal*	
Polarization options	Horizontal,* vertical, or circular	
Tilt, main beam above horizontal	-90° to 90°	______ deg
Tracking	Directional* or tracking	

Table 2. Parameter Specification, General (con't)

	Range	Value
Frequency fraction (half-bandwidth)	0 to 0.2 (0.1)*	________
Gain, receiving antenna (main beam)	0* to 60 dBi	________ dBi
Transmitting antenna (main beam)	0* to 60 dBi	________ dBi
Transmitting antenna location	Aircraft or facility*	
Horizon obstacle distance from facility	From 0.1 to 3 times smooth earth horizon distance (calculated)*	________ km, n mi, s mi
Elevation angle above horizontal at facility	<12 deg (calculated)*	________ deg
Height above msl	0* to 15,000 ft-msl (4572 m-msl) and ≤ aircraft altitude	________ ft, m
Ionospheric scintillation options	No scintillation* or specified	
Frequency scaling factor	Not used* or (136/frequency in MHz)^n with $1 \le n \le 2$	
Index group	0* to 5, 6 for variable	________
Rain attenuation options	None* or computed with dB/km or zone	
Attenuation/km	0 dB/km and up	________ dB/km
Storm size	5, 10,* 20 km	
Zone	1 to 6	________
Refractivity		
Effective earth's radius	4010 to 6070 n mi (7427 to 11,242 km)	________ km, n mi, s mi
or minimum monthly mean, N_o	200 to 400 N-units (301 N-units)*	________
Surface reflection lobing options	Contributes to variability* or determines median level	

Table 2. Parameter Specification, General (con't)

	Range	Value
Surface type options	Poor, average* or good ground, fresh or sea water, concrete, metal	
Sea state	0-glassy,* 1-rippled, 2-smooth, 3-slight, 4-moderate, 5-rough, 6-very rough, 7-high, 8-very high, 9-phenomenal	
or rms wave height, σ_h	0 to 50 m (164 ft)	______ft, m
Temperature	0, 10,* or 20°C	
Terrain elevation above msl at facility	0* to 15,000 ft-msl (4572 m-msl)	______ft, m
Parameter, Δh	0* or greater	______ft, m
Type options	Smooth* or irregular	
Time availability options	For instantaneous levels exceeded* or for hourly median levels exceeded	
Climates	0*-Continental all year, 1-Equatorial, 2-Continental subtropical, 3-Maritime subtropical, 4-Desert, 6-Continental Temperate, 7a-Maritime Temperate Overland, 7b-Maritime Temperate Overseas	
or time blocks	1, through 8, summer, winter	______

(a) Copies of this table may be used to provide data for computer runs by utilizing the blanks provided in the value column and circling desired options. These parameters are common to most programs. However, additional information is needed for various programs and it may be supplied via tables 3 and 4. If desired and undesired facility parameters are not identical, two table 2 parameter specifications, or appropriate notes on a single copy are required.

(b) Parameters are listed in about the same order as on parameter sheets produced by the various programs [21, figs. 1 through 5]. Parameter sheets produced by the various programs are similar, but not identical since only those parameters relevant to a particular program and run will be listed. For example, if the counterpoise diameter is input as zero, the counterpoise will not be considered and none of the parameters associated with it will be listed on the parameter sheet.

* Values or options that will be assumed when specific designations are not made are flagged by asterisks.

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Table 3. Parameter Specification, Special [21, table 3]

Capability	Program	Parameter and Value(s)*
Power available curves	ATLAS	Aircraft altitudes, up to 25, may be specified to cover airspace required:
Power density curves		________
Transmission loss curves		________
Power available volume	HIPOD	________
Power density volume		________ ft-msl, or m-msl.
Transmission loss volume		
EIRP contours	APODS	
Power available contours		
Power density contours		
Transmission loss contours		
Service volume	SRVLUM	
Signal ratio contours	DURATA	
Power available curves	ATLAS	Time availability: ________ percent. Acceptable values range from 0.01 to 99.99 percent. A value of 95 percent will be used if a value is not specified.
Power density curves		
Transmission loss curves		
EIRP contours	APODS	
Power available contours		
Power density contours		
Transmission loss contours		
Orientation	TWIRL	
Signal ratio contours	DURATA	

Table 3. Parameter Specification, Special (con't)

Capability	Program	Parameter and Value(s)*
Power available volume	HIPOD	Power available:________ dBW.
Power density volume	HIPOD	Power density:________dB-W/sq m
EIRP contours	APODS	
Transmission loss volume	HIPOD	Transmission loss:________dB.
EIRP contours	APODS	EIRP'S, up to 8:________dBW.
Power available contours	APODS	Powers available, up to 8:________dBW.
Power density contours	APODS	Power densities, up to 8:________dB-W/sq m
Transmission loss contours	APODS	Transmission loss, up to 8:________dB
Signal ratio-DD	DUDD	
Service volume	SRVLUM	Station separation:________km, n mi, or s mi.
Signal ratio contours	DURATA	
Signal ratio-S	ATADU	Desired facility-to-aircraft distance:________km, n mi, or s mi.
Orientation	TWIRL	Desired-to-undesired signal ratio:________dB.
Service volume	SRVLUM	
Orientation	TWIRL	Protection point location, up to 6:

NOTE: Azimuth is relative to desired station course line with positive values taken as clockwise, and distance is the desired facility-to-aircraft great circle distance

Azimuth		Distance	
______		______	
______		______	
______	deg	______	km, n mi, or s mi
______		______	
______		______	

*Parameter values required for particular capabilities that are not specified in table 2 may be specified by using the blanks provided here. Circle desired units where multiple units are given.

Table 4. Parameter Specification, Graph Formats [21, table 4]

Capability[a]	Program	Ordinate Lower	Ordinate Upper	Ordinate Increment	Ordinate Units[b]	Abscissa Left Side	Abscissa Right Side	Abscissa Increment	Abscissa Units[b]
Lobing	LOBING	____	____	____	dB	____	____	____	km, n mi, or s mi
Reflection coefficient	LOBING	____	____	____		____	____	____	km, n mi, or s mi
Path length difference	LOBING	____	____	____	m	____	____	____	km, n mi, or s mi
Time delay	LOBING	____	____	____	nsec	____	____	____	km, n mi, or s mi
Lobing frequency -D	LOBING	____	____	____	(Hz/THz)/(km/hr) (Hz/THz)/kts (Hz/THz)/(s mi/hr)	____	____	____	km, n mi, or s mi
Lobing frequency -H	LOBING	____	____	____	(Hz/THz)/(m/min) (Hz/THz)/(ft/min)	____	____	____	km, n mi, or s mi
Reflection point	LOBING	____	____	____	km, n mi, or s mi	____	____	____	km, n mi, or s mi
Elevation angle	LOBING	____	____	____	deg	____	____	____	km, n mi, or s mi
Elevation angle difference	LOBING	____	____	____	deg	____	____	____	km, n mi, or s mi
Spectral plot	LOBING	Plot lobe ____ thru ____, counting from the Horizon[c]							
Power available	ATOA	____	____	____	dBW	____	____	____	deg, km, n mi, or s mi
Power density	ATOA	____	____	____	dB-W/sq m	____	____	____	deg, km, n mi, or s mi
Transmission loss	ATOA	____	____	____	dB	____	____	____	km, n mi, or s mi
Power available curves	ATLAS	____	____	____	dBW	____	____	____	km, n mi, or s mi
Power density curves	ATLAS	____	____	____	dB-W/sq m	____	____	____	km, n mi, or s mi
Transmission loss curves	ATLAS	____	____	____	dB	____	____	____	km, n mi, or s mi
Power available curves	HIPOD	____	____	____	ft or m	____	____	____	km, n mi, or s mi
Power density volume	HIPOD	____	____	____	ft or m	____	____	____	km, n mi, or s mi
Transmission loss volume	HIPOD	____	____	____	ft or m	____	____	____	km, n mi, or s mi
EIRP contours	APODS	____	____	____	ft or m	____	____	____	km, n mi, or s mi
Power available contours	APODS	____	____	____	ft or m	____	____	____	km, n mi, or s mi

Table 4. Parameter Specification, Graph Formats (con't)

Capability[a]	Ordinate					Abscissa			
	Program	Lower	Upper	Increment	Units[b]	Left Side	Right Side	Increment	Units[b]
Power density contours	APODS				ft or m				km, n mi, or s mi
Transmission loss contours	APODS				ft or m				km, n mi, or s mi
Signal ratio -S	ATTADU				dB				km, n mi, or s mi
Signal ratio -DD	CUDD				dB				km, n mi, or s mi
Orientation	TWIRL				deg				km, n mi, or s mi
Service volume	SERVLUM				ft or m				deg
Signal ratio contours	DURATA				ft or m				km, n mi, or s mi

(a) In many cases appropriate graph limit can be adequately selected by the program operator so that values need not always be provided here. However, in such cases the capabilities desired should be indicated (circled), and where required (a,b) units should be specified. A plotting capability guide is provided in table 1.

(b) Circle desired units when multiple units are given. Selections for a particular capability must be consistant; i.e., all English or all metric units.

(c) Any 5 consecutive lobes within 10 lobes of the radio horizon may be specified.

taken either as a common horizon with the lower antenna or as a smooth earth horizon with the same elevation as the lower antenna effective reflecting plane [17, sec. A.4.1; 21, sec. 4.1]. Ranges for other parameters associated with the model are given in table 2.

At 0.1 to 20 GHz, propagation of radio energy is affected by the lower, nonionized atmosphere (troposphere), specifically by variations in the refractive index of the atmosphere [2, 3, 4, 8, 12, 20, 23, 35, 36]. Atmospheric absorption and attenuation or scattering due to rain become important at SHF [17, sec. A.4.5; 23, ch. 7; 36, ch. 3; 42]. The terrain along and in the vicinity of the great circle path between transmitter and receiver also plays an important part. In this frequency range, time and space variations of received signal and interference ratios lend themselves readily to statistical description [20; 28; 31; 36, sec. 10]..

Conceptually, the model is very similar to the Longley-Rice [26] propagation model for propagation over irregular terrain, particularly in that attenuation versus distance curves calculated for the (a) line-of-sight [17, sec. A.4.2], (b) diffraction [17, sec. A.4.3], and (c) scatter (sec. 5) regions are blended together to obtain values in transition regions. In addition, the Longley-Rice relationships involving the terrain parameter Δh are used to estimate radio-horizon parameters when such information is not available from facility siting data [17, sec. A.4.1]. The model includes allowance for

(a) average ray bending [4, (3.44), (3.43), (4.30); 5; 17, p. 44; 36, sec. 4; 44][3],
(b) horizon effects [17, sec. A.4.1],
(c) long-term fading [17, sec. A.4; 36, sec. 10],
(d) facility antenna patterns [17, sec. A.4.2; 21, sec. 4.1],

[3]The numbers in parentheses are equation numbers for the given reference; e.g. [4].

(e) surface reflection multipath [6; 7; 16, p. 17; 17, sec. A.6; 18, sec. CI-D.7],

(f) tropospheric multipath [3; 12, sec. 3.1; 17, sec. A.7; 20; 25, pp. 60, B-2, 119],

(g) atmospheric absorption [15, sec. A.3; 17, sec. A.4.5; 36, fig. 3.1],

(h) ionospheric scintillations [1; 16, sec. 2.5; 18, sec. CVII; 32; 47], and

(i) rain attenuation [11, 27].

The IF-77 model is an extended version of the IF-73 model [17, sec. A]. These extensions include provisions for

(a) sea state (discussion of this extension follows in sec. 3.1),

(b) a divergence factor (sec. 3.2),

(c) a ray length factor for situations where the free-space loss associated with a surface reflected ray may be significantly greater than that associated with the direct ray (sec. 3.3),

(d) an antenna pattern at each terminal (sec. 3.4),

(e) circular polarization (sec. 3.5),

(f) frequency and temperature variations of the complex dielectric constant for water (sec. 3.5),

(g) long-term power fading as a function of time block (sec. 4.2) or radio climatic region (sec. 4.3),

(h) rain attenuation (sec. 4.4),

(i) ionospheric scintillation (sec. 4.5),

(j) an improved method for calculating the transmission loss associated with tropospheric scatter (sec. 5),

(k) an improved estimate of the distance where horizon effects can be neglected (sec. 7),

(l) a free-space loss formulation that is applicable to very high antennas (sec. 8),

(m) a formulation for facility horizon determinations that includes ray tracing (9.2),

(n) ray elevation angle adjustment factors to allow for ray tracing (sec. 10.2),

(o) antenna tracking options (sec. 10.3), and

(p) additional antenna pattern options [21, pp. 85-88].

3. EFFECTIVE REFLECTION COEFFICIENT

The formulations used previously [17, pp. 52-57 and 77-79] for effective reflection coefficient were extended to permit

(a) surface roughness to be specified by sea state (sec. 3.1),

(b) both antennas to be high (e.g., both aircraft) by incorporating allowances for a divergence factor (sec. 3.2) and a ray length factor (sec. 3.3),

(c) both terminals to have a vertical antenna pattern associated with them by using a gain factor (sec. 3.4), and

(d) circular polarization (sec. 3.5) as an option.

3.1 Sea State

The 1977 computer programs allow water surface roughness to be specified by sea state or the root-mean-square (rms) deviation, σ_h, of surface excursions within the limits of the first Fresnel zone in the dominant reflecting plane [17, p. 53; 26, p. 3-23; 36, sec. 5.2.2]. Table 5 provides the relationship between sea state and σ_h that is used in the model.

Values for σ_h provided in table 5 were estimated using significant wave height, $H_{1/3}$, estimates from Sheets and Boatwright [41, table 1] with a formulation given by Moskowitz [29, (1)]; i.e.,

$$\sigma_h = 0.25\ H_{1/3} \tag{1}$$

where σ_h and $H_{1/3}$ have the same units.

Once obtained, values of σ_h are used as they were in IF-73 to calculate "reflection reduction factors" $F_{\sigma h}$ [17, (66)], and $F_{d\sigma h}$ [17, (194) as corrected in Appendix A of this report]. Comparisons of these reflection reduction factor formulations with other formulations and data have been made [18, sec. CI-D.7].

Table 5. Estimates of σ_h for Sea States [18, p. CI-81].

Sea State Code[a]	Descriptive Terms[a]	Average Wave Height Range m (ft)	$H_{1/3}$[b] m (ft)	σ_h[c] m (ft)
0	Calm (glassy)	0 (0)	0 (0)	0 (0)
1	Calm (rippled)	0 - 0.1 (0 - 0.33)	0.09 (0.3)	0.00 (0.08)
2	Smooth (Wavelets)	0.1 - 0.5 (0.33 - 1.6)	0.43 (1.4)	0.11 (0.35)
3	Slight	0.5 - 1.25 (1.6 - 4.0)	1 (3.3)	0.25 (0.82)
4	Moderate	1.25 - 2.5 (4 - 8)	1.9 (6.1)	0.46 (1.5)
5	Rough	2.5 - 4 (8 - 13)	3 (10)	0.76 (2.5)
6	Very rough	4 - 6 (13 - 20)	4.6 (15)	1.2 (3.8)
7	High	6 - 9 (20 - 30)	7.9 (26)	2 (6.5)
8	Very high	9 - 14 (30 - 46)	12 (40)	3 (10)
9	Phenomenal	>14 (>46)	>14 (>45)	3.3 (11)

(a) Based on international meteorological code [30, code 3700].

(b) Estimates significant wave heights (average of highest one-third, $H_{1/3}$ [41, table 1]).

(c) Estimated using a formulation provided by Moskowitz [29, (1)] with $H_{1/3}$ estimates.

3.2 Divergence Factor

The divergence factor, D, is used to allow for the divergence of energy reflected from a curved surface in the effective reflection coefficient formulation. It is defined by Reed and Russell [35, p. 103] "as the ratio of the field strength obtained after reflection from a spherical surface to that obtained after reflecting from a plane surface, the radiated power, total axial distance, and type of surface being the same in both cases, and the solid angle being a small elemental angle approaching zero in magnitude."

Figure 1 illustrates the geometry for reflection from a plane earth and a spherical earth where the relative location of the source reflecting point and reference plane are identical. It also shows the relative size of the ray bundle on the reference plane for each case (see fig. 1. caption). The divergence factor is related to the reference plane area associated with the spherical earth reflection, A_{se}, and the plane earth reflection, A_{pe}, by

$$D = \sqrt{A_{pe}/A_{se}} \;. \tag{2}$$

Derivations of expressions for D are beyond the scope of this text, but such developments are available [7, sec. 11.3; 8, pp. 95-97; 23, sec. 5.2; 35, sec. 4.27; 36]. An exact expression for D that is very similar to the formula provided by Beckmann and Spizzichino [7, p. 223] may be developed by extending the Riblet and Barker formulation [37, (13)] to the special case where principal radii of curvature of the reflecting surface at the reflection point are within, a_p, and normal, a_n, to the plane of incidence. This expression is

$$D = \left[1 + \frac{2r_1 r_2}{a_p (r_1 + r_2) \sin\psi}\right]^{-1/2} \left[1 + \frac{2r_1 r_2 \sin\psi}{a_n (r_1 + r_2)}\right]^{-1/2} \tag{3}$$

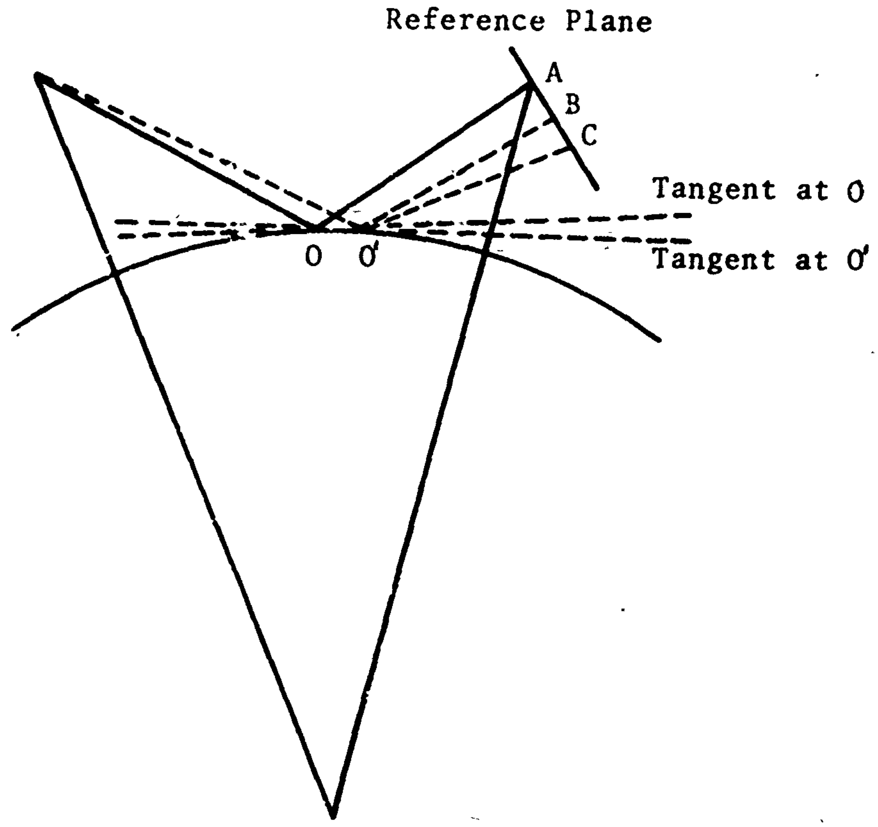

Figure 1. Sketch illustrating divergence. Line length AB indicates ray bundle size at the reference plane for reflection from a plane surface and AC corresponds to reflection from the curved surface.

where the ray lengths r_1 and r_2 along with the grazing angle ψ are shown in figure 2. Here the $r_{1,2}$[4] and $a_{n,p}$ must be expressed in the same units; e.g., kilometers. For the spherical earth case, $a_p = a_n = a_a$, so that (3) may be expressed as

$$D = \left[1 + \frac{2R_r(1 + \sin^2 \psi)}{a_a \sin \psi} + \left(\frac{2R_r}{a_a}\right)^2\right]^{-1/2} \tag{4}$$

where

$$R_r = r_1 r_2/(r_1+r_2) \,. \tag{5}$$

Values for ψ are obtained as in IF-73 [17, p. 58], and values for $r_{1,2}$ are calculated using

$$r_{1,2} = \begin{cases} H_{1,2} \text{ if } \psi \approx 90^\circ \\ D_{1,2}/\cos \psi \text{ otherwise} \end{cases} \tag{6}$$

where $H_{1,2}$ and $D_{1,2}$ are defined by figure 2. A formula for $D_{1,2}$ is included in IF-73 [17, p. 51].

Divergence, as calculated using (4), is used in IF-77. It is incorporated into IF-73 as a factor multiplying the left-hand side of equation [17, (68)].

3.3 Ray Length Factor

The ray length factor, F_r, is used to allow for situations where the free-space path loss associated with the reflected ray may be significantly greater than that associated with the direct ray. It is determined using

$$F_r = \frac{r_o}{r_{12}} \tag{7}$$

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[4]This notation, $r_{1,2}$, is used to imply r_1 or r_2.

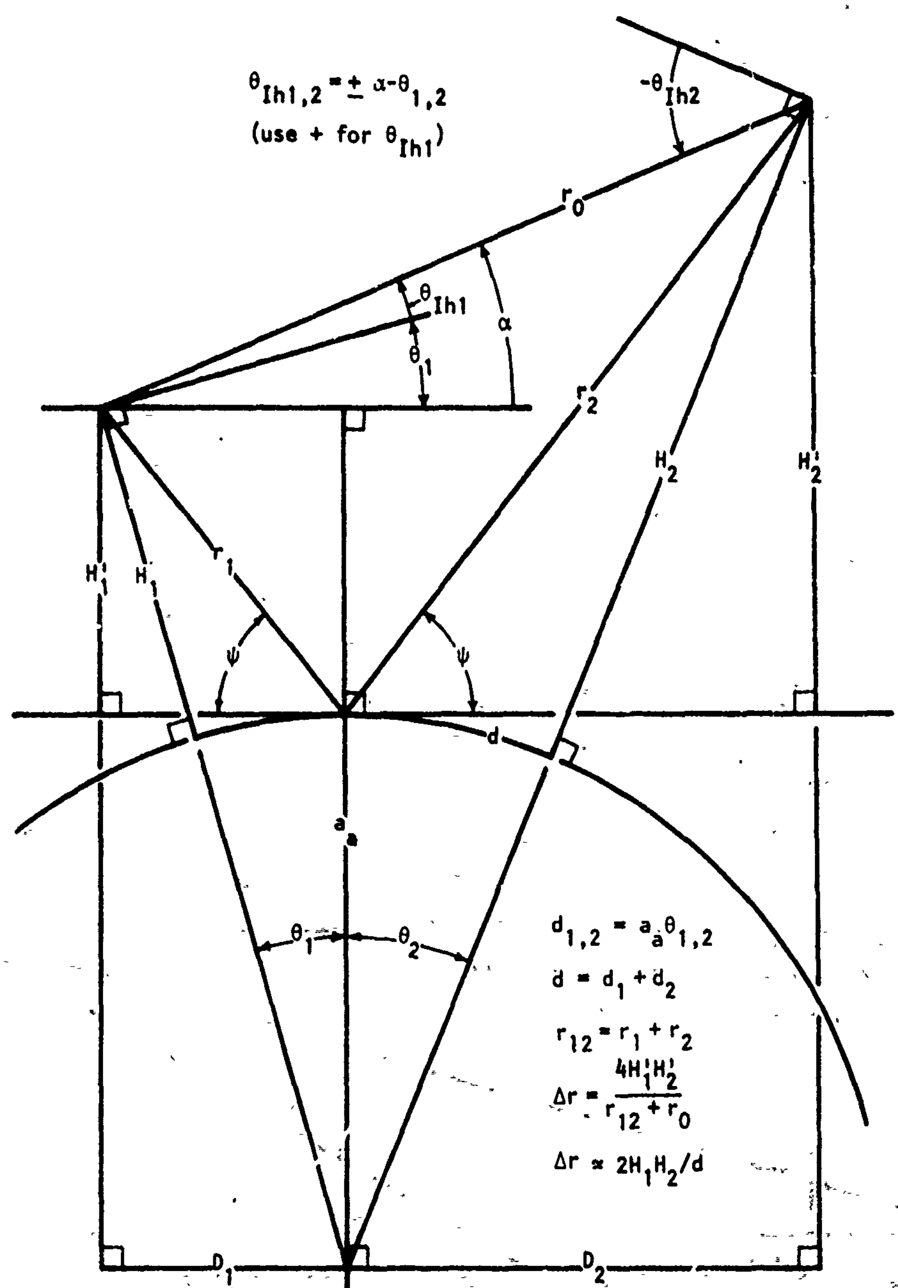

Figure 2. Spherical earth geometry (not drawn to scale). Relationships between the various geometric parameters shown here were previously provided in IF-73 [17, sec. A.4.2].

where r_o is the direct ray length and r_{12} is the reflected ray length $(r_1 + r_2)$ as illustrated in figure 2. Incorporation into IF-73 is accomplished by using it as a multiplying factor to the left-hand side of equation [17, (68)].

3.4 Gain Factors

The antenna gain factors $g_{D,R}$ and $g_{Rh,v}$ are used to allow for situations where the antenna gains effective for the direct ray path differ from those for the reflected ray path. Figure 3 illustrates the two-ray path and indicates the gains involved. These are the relative voltage antenna gains (volts/volt or V/V) associated with the direct ray at terminal one or two, $g_{D1,2}$, and those associated with the reflected ray, $g_{R1,2}$. They are measured relative to the main beam of their respective terminal antenna; i.e., for main beam conditions $g_{D,R} = g_{R1,2} = 1$ V/V. This convention is consistent with usage in IF-73 [17, p. 39]. However, it is NOT CONSISTENT with usage in the Multipath Handbook [18, sec. CI-D.3] where identical symbols are used, but the gains are measured relative to an isotropic antenna.

In general, these gains are complex quantities, but IF-77 includes provisions for scalar gains only. In many practical applications the direct and reflected rays will leave (or arrive) at

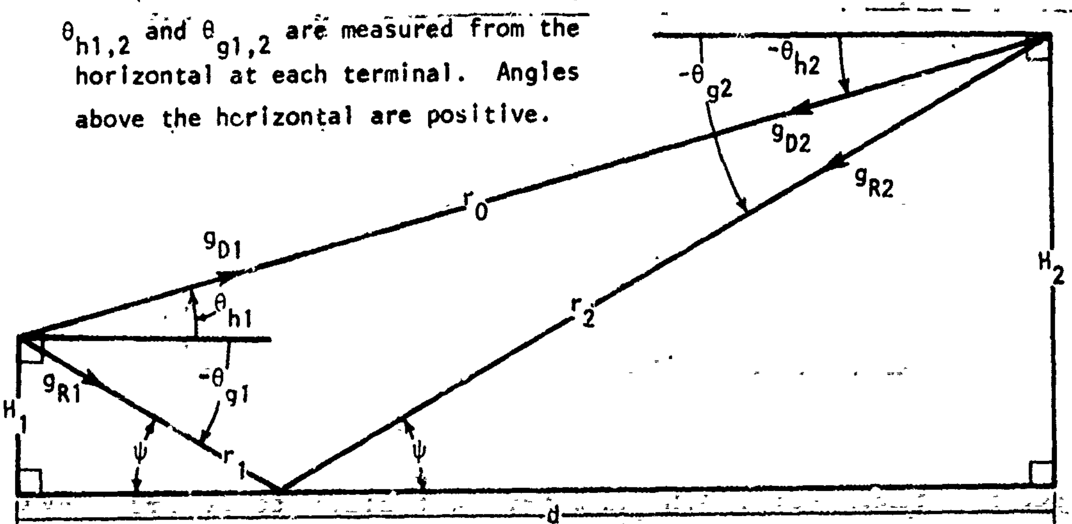

Figure 3. Sketch illustrating antenna gain notation (not drawn to scale).

elevation angles where the relative phase is either expected to be near zero or is unknown, so that the complex nature of these gains is largely academic. They are called voltage gains since they are a voltage ratio that could be considered dimensionless (volt/volt), but are different from gains expressed as power ratios (watt/watt) that could also be considered dimensionless. Decibel gains above main beam values are related to these gains by formulas such as

$$G_{R1,2}[\mathrm{dB}] = 20 \log |g_{R1,2}| \tag{8}$$

and

$$|g_{R1,2}|[\mathrm{V/V}] = 10^{(G_{R1,2}/20)}. \tag{9}$$

The formulations for $g_{D,R}$ are

$$g_D[\mathrm{V/V}] = \begin{Bmatrix} g_{D1}\ g_{D2} \text{ for linear polarization} \\ 0.5[g_{hD1}\ g_{hD2} + g_{vD1}\ g_{vD2}] \text{ for circular polarization} \end{Bmatrix} \tag{10}$$

and

$$g_R[\mathrm{V/V}] = \begin{Bmatrix} 1 \text{ for omnidirectional antennas and/or circular polarization (see text below)} \\ g_{R1}\ g_{R2} \quad \text{otherwise} \end{Bmatrix} \tag{11}$$

where omnidirectional implies that, for the radiation angles of interest, $g_{R1} = g_{D1}$ and $g_{R2} = g_{D2}$. In problems involving circular polarization, horizontally polarized ($g_{hD1,2}$ and $g_{hR1,2}$) and vertically polarized ($g_{vD1,2}$ and $g_{vR1,2}$) components are used. Linear polarization is considered to be either vertical or horizontal with the polarization associated with $g_{D,R}$ selected accordingly. Defining g_R as 1 for circular polarization is done to allow the antenna gains to be included in the reflection coefficient formulation of IF-77 in a simple way for horizontal or vertical polarization. The circular polarization case will be discussed in the next section.

The IF-73 was extended to include g_R by incorporating it as a replacement for the multiplying factor g in left-hand side of two equations [17, (68), (69)]. For special cases where only the antenna patterns of IF-73 are used (i.e., isotropic aircraft antenna pattern and specific facility antenna patterns), g_R reduces to g [17, (67)]. The effects of g_D are included in IF-73 [17, (81), (82)] with a variable named g_D, but since g_D can now be complex, it is necessary to use $|g_D|$ in one of the IF-73 equations [17, (82)]. In addition, it should be realized that the aircraft antenna gain is not necessarily 0 dBi as it was in IF-73 [17, p. 37].

The gain factor g_{Rv} is similar to g_R except that g_{Rv} involves gains $g_{vR1,2}$; i.e.,

$$g_{Rv}[V/V] = \begin{cases} 1 \text{ for omnidirectional antennas} \\ g_{vR1}\ g_{vR2} \quad \text{otherwise} \end{cases} . \tag{12}$$

Also

$$g_{Rh}[V/V] = \begin{cases} 1 \text{ for omnidirectional antennas} \\ g_{hR1}\ g_{hR2} \quad \text{otherwise} \end{cases} \tag{13}$$

where g_{Rh} is for horizontal polarization. These factors will be used in the formulation of complex plane earth reflection coefficients for circular polarization that is given in the next section.

3.5 Plane Earth Reflection Coefficient

Values for the complex plane earth reflection coefficient, R exp(-jΦ), used in IF-73 [17, pp. 52, 53] depend on the relative dielectric constant, ε, and conductivity, σ, along with wavelength, λ, grazing angle, ψ, and polarization [7, p. 219; 18, sec. CI-D.8; 23, p. 396; 35, p. 88; 36, sec. III.1]. For vertical polarization (electric field in the plane of incidence)

or horizontal polarization (electric field normal to plane of incidence) $R \exp(-j\phi)$ is given by

$$R_v \exp\left[-j(\pi - c_v)\right] = \frac{\varepsilon_c \sin(\psi) - Y_c}{\varepsilon_c \sin(\psi) + Y_c} \, g_R \tag{14}$$

or

$$R_h \exp\left[-j(\pi - c_h)\right] = \frac{\sin(\psi) - Y_c}{\sin(\psi) + Y_c} \, g_R, \tag{15}$$

respectively, where

$$Y_c = \sqrt{\varepsilon_c - \cos^2\psi} \tag{16}$$

is complex, the complex relative dielectric constant, ε_c, is defined as

$$\varepsilon_c = \varepsilon - j\ 60\lambda\sigma, \tag{17}$$

and g_R is from (11).

In IF-77, linear polarization gain factors (sec. 3.4) and reflection coefficients are combined to obtain a reflection coefficient formulation for circular polarization; i.e.,

$$R_c \exp\left[-j(\pi-c_c)\right] = 0.5\left[g_{Rh} R_h \exp\left[-j(\pi-c_h)\right] + g_{Rv} R_v \exp\left[-j(\pi-c_v)\right]\right]. \tag{18}$$

This formulation is used only for antennas with the same polarization sense (e.g., both right-handed).

For a perfect dielectric ($\sigma = 0$ so that $\varepsilon_c = \varepsilon$), the numerator of (14) will go to zero when $\psi = \psi_B$ where

$$\psi_B = \mathrm{Sin}^{-1}\sqrt{1/(\varepsilon + 1)} \tag{19}$$

so that $R_v = 0$. This critical angle is called the Brewster angle and a similar angle associated with reflection from a surface that has non-zero conductivity is called the pseudo-Brewster angle [36, sec. III.1]. Equation (19) may be used to estimate the pseudo Brewster angle when $\varepsilon > 60\lambda\sigma$. Figure 4 shows the dip

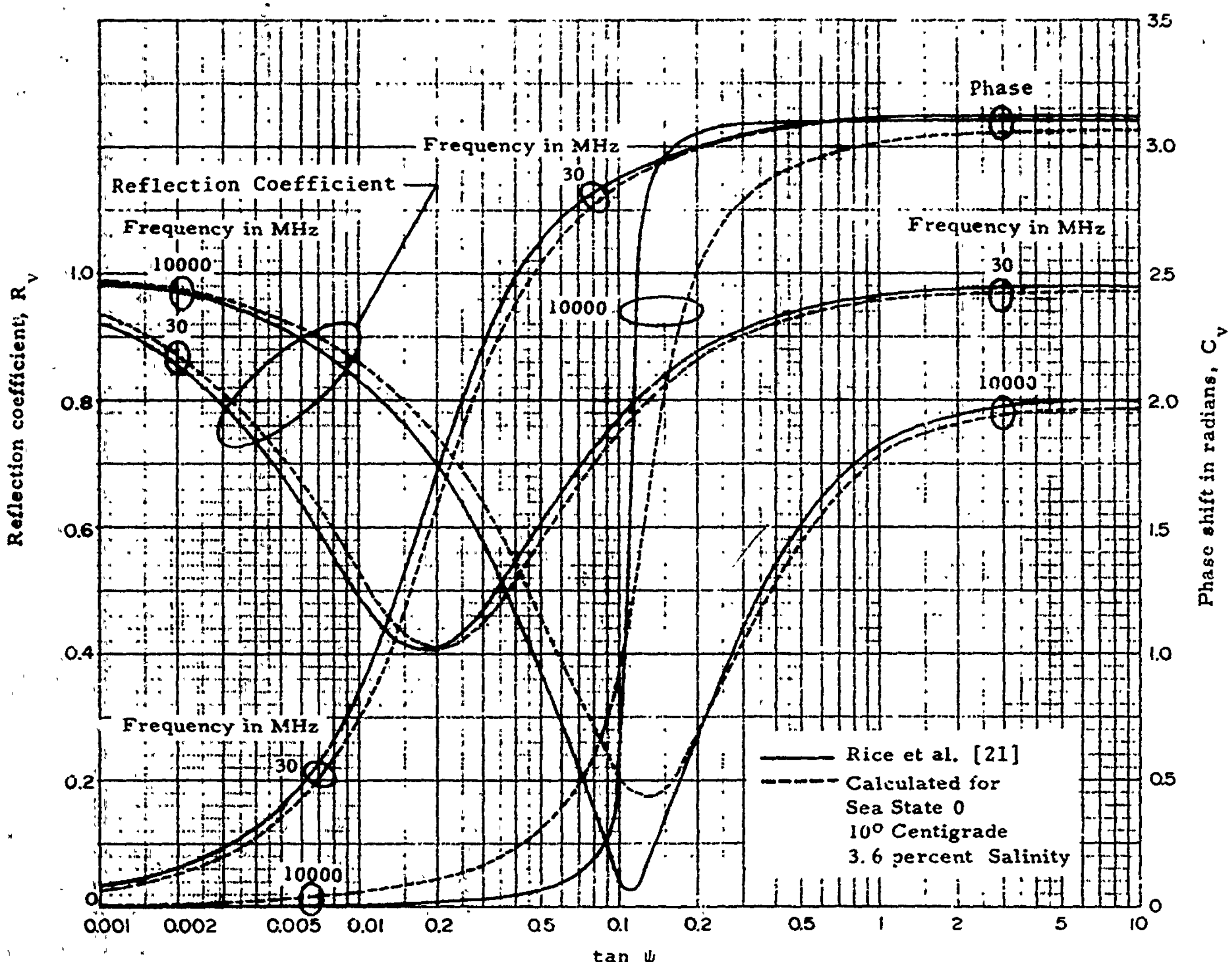

Figure 4. Comparison of reflection coefficients for sea water, vertical polarization [18, p. CI-103].

in the reflection coefficient for vertical polarization associated with the pseudo-Brewster angle along with the abrupt change in phase that occurs as ψ goes through its critical value. This change in phase, which does not occur for horizontal polarization, will change the rotation sense of circularly polarized waves that are reflected from the surface; i.e., when a circularly polarized wave is reflected, its rotation sense will remain unchanged only if the grazing angle is less than the pseudo-Brewster angle.

In IF-77, ε and σ for water may be estimated with

$$\varepsilon = \frac{\varepsilon_s - \varepsilon_o}{1 + (2\pi f T)^2} + \varepsilon_o \tag{20}$$

and

$$\sigma\ [\text{mho/m}] = f^2 T(\varepsilon - \varepsilon_o)/2865 + \sigma_i \tag{21}$$

where ε_s is the static dielectric constant, $\varepsilon_o = 4.9$ is the dielectric constant representing the sum of electronic and atomic polarizations, f[MHz] is frequency, T[μs] is relaxation time, and σ_i(mho/m] is the ionic conductivity. Values of ε_s, T, and σ_i obtained using Saxton and Lane [40] are provided in table 6 for fresh water and sea water.

Figure 4 provides a comparison of reflection coefficients calculated using the fixed values (table 6) of surface constant given by Rice et al. [36, p. III-7] for sea water (solid lines) with those determined via calculated surface constants (dashed lines). More such comparisons are available [18, sec. CI-D.8].

4. VARIABILITY

Model extensions that are concerned directly with transmission loss (or received signal level) variability are discussed in this section. These extensions include provisions for (1) mixing distributions (sec. 4.1), (2) computing long-term variability for various time blocks (sec. 4.2) or climates (sec. 4.3), and (3) estimating the effects of rain attenuation (sec. 4.4) and ionospheric scintillation (sec. 4.5).

Table 6. Surface Types and Nominal Constants

Surface Type	ε	σ[mho/m]
Poor Ground[a]	4	0.001
Average Ground[a]	15	0.005
Good Ground[a]	25	0.02
Fresh Water[a]	81	0.01
Sea Water[a]	81	5
Concrete[b]	5	0.01
Metal[c]	10	10^7

For Fresh Water

	0°C	10°C	20°C
ε_s [d]	88	84	80
$T[\mu s]$ [d]	1.87×10^{-5}	1.36×10^{-5}	1.01×10^{-5}
σ_i [mho/m] [a]	0.01	0.01	0.01

For Sea Water[e]

	0°C	10°C	20°C
ε_s	75	72	69
$T[\mu s]$	1.69×10^{-5}	1.21×10^{-5}	9.2×10^{-6}
σ_i [mho/m]	3.0	4.1	5.2

[a] From Longley and Rice [26, table 2].
[b] Estimated [23, p. 398].
[c] Estimated [34, p. 235, p. 240].
[d] From Saxton and Lane for 0% salinity [40, table 1].
[e] From Saxton and Lane for 3.6% salinity [40, table 1].

4.1 Mixing Distributions

Subroutines have been incorporated into the computer programs to allow the distributions that characterize portions of the variability associated with a particular model component to be mixed in order to obtain the total variability for that component. For example, different fractions of the time may be characterized by signal level distributions associated with different ionospheric scintillation groups, and, with these subroutines, they can be weighted and combined (mixed) to obtain the total variability associated with ionospheric scintillations (sec. 4.5).

The process of mixing N cumulative variability distributions may be summarized as follows:

1) Select M (ten or more) levels of variability $V_1, \ldots, V_i, \ldots, V_M$ that cover the entire range of the transmission loss (or power available, etc.) values involved.
2) Determine the fraction of time (weighting factor) for which each distribution is applicable; i.e., $W_1, \ldots, W_j, \ldots, W_N$.
3) Determine the time availability (fraction of time during which a distribution is applicable that a specific level of transmission loss is not exceeded) for each distribution at the selected levels; i.e., $q_{11}, \ldots, q_{ij}, \ldots, q_{MN}$.

and 4) Calculate time availabilities for the mixed distribution that corresponds to the variability levels selected, i.e.,

$$
\begin{aligned}
q_1 &= q_{11} W_1 + \ldots + q_{1j} W_j + \ldots + q_{1N} W_N \\
&\vdots \\
q_i &= q_{i1} W_1 + \ldots + q_{ij} W_j + \ldots + q_{iN} W_N \qquad (22) \\
&\vdots \\
q_M &= q_{M1} W_1 + \ldots + q_{Mj} W_j + \ldots + q_{MN} W_N .
\end{aligned}
$$

This process is the same as the one used by Rice et al. [36, sec. III.7.2] to combine transmission loss distributions for time blocks (sec. 4.2) to obtain distributions for summer and winter. It is also essentially the same as the method recommended by Whitney et al. [46, p. 1099; 47, sec. 6] to combine distributions of fading associated with various ionospheric scintillation index groups (sec. 4.5).

When this process is used to mix distributions of long-term variability, the required variability functions are obtained from

$$V_c(q) = V(0.5) + Y(q)|_c \tag{23}$$

where $|_c$ indicates that the V(0.5) and Y(q) are appropriate for the conditions (time block or climate) associated with a particular value of the subscript c. For example, V(0.5) and Y(q) values for different climates can be obtained with the information supplied in section 4.3, and mixing can be used to estimate variability for areas near a border between two different climate types. After mixing, Y(q) values needed for later calculations may be obtained from using

$$Y(q) = V(q) - V(0.5) \tag{24}$$

where all variables in (24) are associated with the resulting mixed distribution. Similarly, when mixing variabilities associated with ionospheric scintillation,

$$Y_{Ic}(q) = Y_I(q)|_c, \tag{25}$$

and the distribution resulting from the mixing is taken as $Y_I(q)$ for later calculations.

4.2 Time Blocks

The long-term variability portion of IF-73 [17, sec. 4.5] has been extended to allow the variability associated with specific time blocks or a combination of time blocks (sec. 4.1) to be used. Table 7 shows the months and hours of the day that correspond to the various time blocks. These blocks and season groupings are used to describe the diurnal and seasonal variability in a continental temperate climate [36, sec. III.7.1].

Table 7. Time Block Ranges [36, sec. III.7.1].

No.	Months	Hours
1	Nov. - Apr.	0600 - 1300
2	Nov. - Apr.	1300 - 1800
3	Nov. - Apr.	1800 - 2400
4	May - Oct.	0600 - 1300
5	May - Oct.	1300 - 1800
6	May - Oct.	1800 - 2400
7	May - Oct.	0000 - 0600
8	Nov. - Apr.	0000 - 0600
Summer	May - Oct.	all-hours
Winter	Nov. - Apr.	all-hours

Variability associated with the time blocks and seasons given in table 4 were incorporated into IF-77 by allowing the constants given by Rice et al. [36, tables III.2, III.3, and III.4] to be used in an equation of IF-73 [17, (178)].

4.3 Climates

The IF-77 includes extensions that allow the use of long-term power fading (variability) applicable to various climates. However, the long-term variability of IF-73 [17, sec. A.5] is normally used in IF-77 except when another climate, time block, (sec. 4.2) or combination (sec. 4.1) of climates (or time blocks) is specifically requested. The ability to mix distributions (sec. 4.1) that characterize long-term power fading to obtain combinations of climates or time blocks [36, sec. III.7.2] adds flexibility to the model. For example, (a) more meaningful comparisons can be made with data in cases where the data collected do not represent all hours of the day or all months of the year [14, sec. 4.3], and (b) variability formulations that may become available for propagation via specific mechanisms

(forward scatter, diffraction, partial reflections, ducting, etc.) can be combined in accordance with the fraction of the total time that they are effective.

The various climate types are listed in table 8 , including supplementary data to aid in the selection of the appropriate type for a specific radio link. Table 8 (Samson and Hart, DOC-BL, informal communication) is based primarily on the annex to CCIR Report 244-2 [10], and is presented here as the best available information in lieu of maps. If a path is near a border between two different climate types, calculations can be made for each climate or mixing (sec. 4.1) can be performed to combine the variabilities associated with the climates involved.

The formulation for long-term variability given here as a function of effective distance, d_e [17, (177) on p. 75], is based on curves provided in CCIR Report 244-2 [10]. Algebraic expressions fitted to the modified versions of the CCIR curves are used (Hufford and Longley, DOC-BL, informal communication). It was felt that the CCIR estimates for Climates 3, 7a, and 7b are not typical for longer distances and values of time availability of 1 percent or less; i.e., time fraction of $q \leq 0.01$. The near free-space values shown by the CCIR curves for paths with $d_e \geq 400$ km require that the signal be carried within a duct, and while this could occur, it is not considered typical enough to be included in a general variability formulation. Thus, curves developed from the formulation provided here would differ somewhat from the applicable CCIR recommendations and reports, but they are thought to be improved estimates. A more complete discussion of this formulation that includes graphs for various climates has been prepared for publication in a Military Handbook (MIL HDBK 417) titled "Facility Design Handbook for Transhorizon Communications".

The formulation is incorporated into computer programs via

Table 8. Climate Types and Characteristics

CCIR Climate	Radio-Climate Designator	Approximate Latitude Range	Seasonal Temperature (°F) Variation	Absolute Humidity (Surface)	Annual Precipitation Inches (cm)	Seasonal Variation in Precipitation	Wind	Typical Mean Annual N_s Near sea-level N-units	Annual Range of Monthly Mean N_s	Remarks
1	Equatorial	10°N-10°S	Small	High all seasons	40-100 (102-254)	Maxima near equinoxes (Mar. 21 - Sept. 23); no completely dry season.	Prevailing easterlies; frequent calms.	360	0- 30	Shower type rain predominates; any anomalous propagation occurs in stable periods between showers.
2	Continental sub-tropical	10°-20°	Moderate	Winter: moderate to high; summer: high	10-100 (25-254)	Dry winter, rainy summer.	Monsoonal shift in direction.	320	60-100	Where land is dry, ducts may form at times most of year.
3	Maritime sub-tropical	10°-20°	Moderate	High	10-100 (25-254)	Dry winter, rainy summer.	Monsoonal shift in direction.	370	30- 60	Usually lowlands near sea.
4	Desert	20°-30°	Very large	Very low	<10 <(25)	Dry all seasons, large year-to-year variations.		280	20- 80	Scatter propagation poor, especially in summer.
5	Mediterranean	30°-40°	Moderate (mild winters and hot summers)	Moderate to high	15- 35 (38- 89)	Very dry summer; most rain in winter.	Variable	320	10- 30	These regions close to the sea; many are subject to elevated ducting in dry season.
6	Continental temperate	30°-60°	Very large	Varies greatly with air mass changes; highest in summer.	15- 45 (38-114)	Spring & summer thunder-showers, winter snow. Prevailing winds off-shore (land to sea); shielded by mountains from on-shore moist winds.	Variable	320	20- 40	Affected by moving storms, fronts, and pressure systems. Sheltered from sea or large lake influences, N_s in plateau areas may be 250-280.
7a	Maritime temperate, Overland	30°-60°	Moderate	Moderate to high (varies with wind direction & air mass changes)	25-100 (64-254)	Driest season tends to be spring or summer; high rain-fall coastal mountains.	Prevailing winds off sea & unobstructed by mountains; flow off land mass brings lowest humidity. May be significant land-sea breeze effects.	320	20- 30	Typical areas are west coast of continents or large island in latitudes of westerlies (United Kingdom, west Europe west coast N. America), Japan more nearly climate 6.
7b	Maritime temperate, Oversea	30°-60°	Moderate	High	25- 60 (64-152)			320	20- 30	Applies to coastal & oversea areas where both horizons of path are on sea. Ducts may occur frequently.
8	Polar	60°-90°	Very large	Low	5- 15 (13- 38)	Winter snow very dry; most precipitation in summer showers.		300	10- 40	

$$\left.\begin{matrix} V(0.5) \\ Y_o(0.1) \\ -Y_o(0.9) \end{matrix}\right\} = \frac{(d_e/b_1)^2}{1+(d_e/b_1)^2}\left[c_1 + \frac{c_2}{1+[(d_e-b_2)/b_3]^2}\right] \tag{26}$$

$$Y(0.1) = Y_o(0.1)\ g(0.1,f) \tag{27}$$

and

$$Y(0.9) = Y_o(0.9)\ g(0.9,f) \tag{28}$$

where values obtained are used as in IF-73 for V(0.5) [17, (190)], Y(0.1)[17, (180)], and Y(0.9)[17, (181)]. Effective distance, d_e, is determined as it was in IF-73 [17, (177)]; values for the constants b_1, b_2, b_3, c_1, and c_2 to be used for each climate are provided in table 9 and the factors g(0.1,f) and g(0.9,f) are calculated as follows:

$$g(0.1,f) = \left\{\begin{array}{l} 1 \text{ for all climates except 2,4, and 6,} \\ 0.18 \sin 5 \log_{10}(f/200) + 1.06 \\ \quad \text{for } 60 \leq f \leq 1500 \text{ MHz in Climates 2 and 6,} \\ 1 \text{ suggested for } 60 \leq f < 200 \text{ MHz in Climate 4,} \\ 0.10 \sin 5 \log_{10}(f/200) + 1.02, \\ \quad \text{for } 200 \leq f \leq 1500 \text{ MHz in Climate 4,} \\ 0.93 \text{ for } f > 1500 \text{ MHz in Climates 2,4, and 6} \end{array}\right\} \tag{29}$$

and

$$g(0.9,f) = \left\{\begin{array}{l} 1 \text{ for all climates except 6,} \\ 0.13 \sin[5 \log_{10}(f/200)] + 1.04 \\ \quad \text{for } 60 \leq f \leq 1500 \text{ MHz in Climate 6,} \\ 0.92 \text{ for } f > 1500 \text{ MHz in Climate 6} \end{array}\right\}. \tag{30}$$

Note that the above formulation is incomplete in some respects, but that approximations are suggested to fill the gaps; i.e., (a) g(0.1,f) in (29) is approximated by 1 for $60 \leq f < 200$ MHz in Climate 4, and (b) the constants for Climate 8 (table 9) are approximated with those of Climate 6.

Table 9. Constants Used to Calculate V(0.5), $Y_o(0.1)$, and $Y_o(0.9)$

Climate	Parameter	b_1	b_2	b_3	c_1	c_2
1. Equatorial	V(0.5)	144.9	190.3	133.8	-9.67	12.7
	$Y_o(0.1)$	636.9	134.8	95.6	2.70	131.1
	$Y_o(0.9)$	762.2	123.6	94.5	-2.73	-204.4
2. Continental subtropical	V(0.5)	228.9	205.2	143.6	-0.62	9.19
	$Y_o(0.1)$	138.7	143.7	98.6	8.8	19.9
	$Y_o(0.9)$	100.4	172.5	136.4	-3.41	-9.83
3. Maritime subtropical	V(0.5)	262.6	185.2	99.8	1.26	15.5
	$Y_o(0.1)$	165.3	225.7	129.7	12.9	12.3
	$Y_o(0.9)$	138.2	242.2	178.6	-7.83	-8.52
4. Desert	V(0.5)	84.1	101.1	98.6	-9.21	9.05
	$Y_o(0.1)$	464.4	93.1	94.2	4.72	204.2
	$Y_o(0.9)$	139.1	132.7	193.5	-2.54	-16.8
5. *Mediterranean	-----	-----	-----	-----	-----	-----
6. Continental temperate	V(0.5)	228.9	205.2	143.6	-0.62	9.19
	$Y_o(0.1)$	93.2	135.9	113.4	6.04	10.4
	$Y_o(0.9)$	93.7	186.8	133.5	-3.43	-9.17
7a. Maritime temperate	V(0.5)	141.7	315.9	167.4	-0.39	2.86
	$Y_o(0.1)$	216.0	152.0	122.7	11.0	17.9
overland	$Y_o(0.9)$	187.8	169.6	108.9	-8.79	-13.3
7b. Maritime temperate	V(0.5)	2222.0	164.8	116.3	3.15	857.9
	$Y_o(0.1)$	136.2	188.5	122.9	10.8	10.5
oversea	$Y_o(0.9)$	609.8	119.9	106.6	-10.9	-217.6
8. *Polar		Use climate 6				

* For climates numbers 5 and 8, Mediterranean and Polar, values are not available; a substitute for Polar is suggested for use unless more definite information is available from other sources.

After Y(0.1) and Y(0.9) have been obtained with (27) and (28), other levels of the distribution are calculated using

$$Y(q) = cY(0.1) \text{ for } q < 0.5 \qquad (31)$$

and

$$Y(q) = cY(0.9) \text{ for } q > 0.5 \qquad (32)$$

where the values for c are obtained from tables 10 and 11. These c values have been extended to include those associated with the long-term variability formulation of IF-73 so that (31) and (32) can be used with it.

Table 10. The Factor c for $q<0.1$ to be used in (31)

Climate Number	q = 0.01	q = 0.001	q = 0.001
1, 6 & 8*	1.95	2.73	3.33
2	1.79	2.27	2.66
3	2.20	3.30	3.70
4	1.82	2.41	2.90
5*	----	----	----
7a & 7b	2.15	3.05	3.80

*See table 6.

Table 11. The Factor c for $q > 0.9$ to be Used in (32).

q	c*
0.95	1.28
0.99	1.82
0.995	2.01
0.999	2.41
0.9995	2.57
0.9999	2.90

*For $q>0.9$ c values follow a log-normal distribution for all climates.

4.4 Rain Attenuation

The rain attenuation model used in IF-77 is largely based on material in informal papers by C. A. Samson (DOC-BL) on "Radio propagation through precipitation" and "Rain rate distribution curves". Only those portions of these papers that are directly related to IF-77 are repeated here. However, an attempt has been made to cite references on which his work is based.

Two options for rain attenuation are available in IF-77. The first is for use in a "worse case" type analysis where a particular rainfall attenuation rate is assumed for the in-storm path length, and the additional path attenuation associated with rain is simply taken as the product of this attenuation rate (in dB/km) and the in-storm ray length. This ray length is determined in accordance with the method discussed as step 4 of option two.

Option two involves computer inputs of rain zone (which determines a rainfall rate distribution) and storm size. Rain zones may be estimated using figure 5 or 6, and the storm size (diameter or long dimension) is assumed to be one of three options: 5, 10, or 20 km (corresponding approximately to a relatively small, average, or very large thunderstorm). The maximum distance used in calculating path attenuation with this option is the storm size since it is assumed that only one storm is on the path at a time. The process used to include rain attenuation estimates in IF-77 for this option may be summarized as follows:

1) <u>Determine point rain rates</u>. Point rain rates (rate at a particular point of observation) not exceeded for specific fractions of the time are determined from table 12 for the rain zone of interest. Values listed in this table were taken from estimated distributions [22; 38; 39; 45].

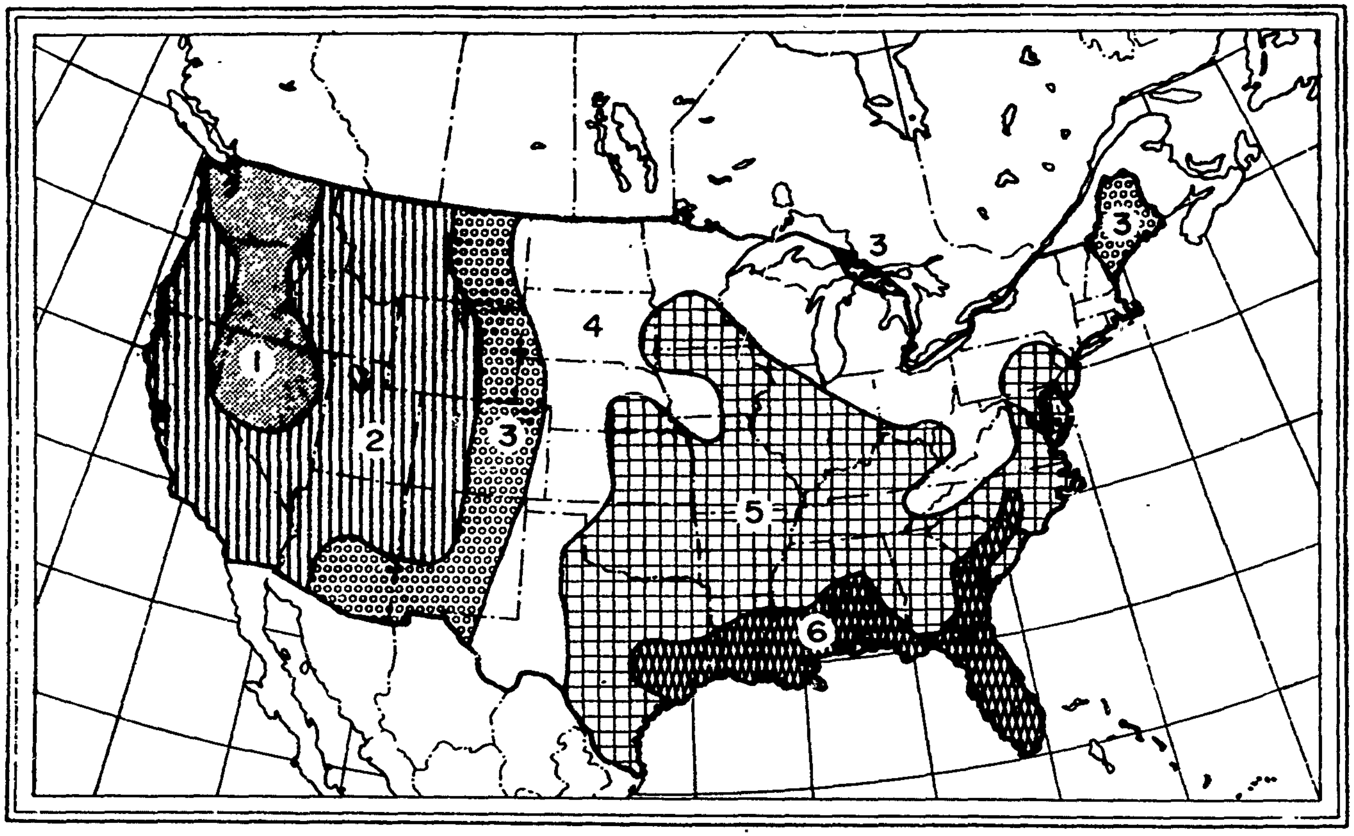

Figure 5. Rain zones of the continental United States [42, fig. 10]; i.e., 5-min rainfall rates expected to occur once in 2 years on the average. Values in inches/hr; e.g., area 5 ranges from 4 1/2 to 5 1/2 in/hr (110 to 140 mm/hr). Rain rates of 1, 2, 3, 4, 5, and 6 in/hr are equivalent to rates of 25, 51, 76, 100, 130, and 150 mm/hr, respectively.

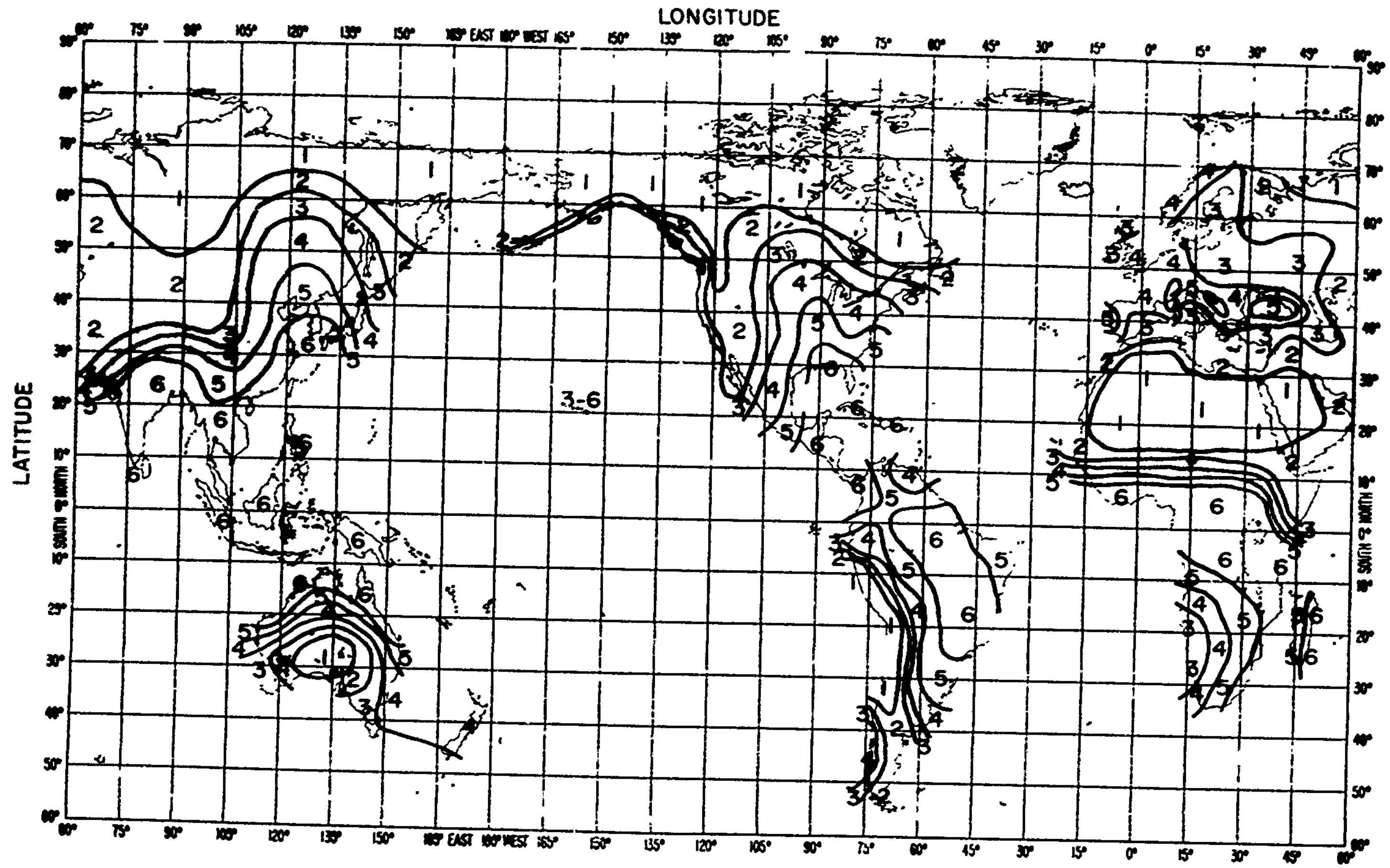

Figure 6. Rain zones of the world (Samson, DOC-BL, informal communication). This map is based on much less data than the figure 5 and should be used only to provide a rough indication of the areas in which rain attenuation may be a significant factor. Zone numbers used here have the same significance as those used in figure 5.

Table 12. Point Rain Rates (mm/hr) not Exceeded for a Fraction of Time, q.

	Rain Zone					
r	1	2	3	4	5	6
≤.98	0	0	0	0	0	0
.99	0.17	0.25	0.31	0.54	0.75	1.0
.995	0.62	0.98	1.54	2.07	2.7	3.35
.998	1.8	3.1	4.8	6.2	7.8	9.4
.999	3.2	5.4	8.8	11.7	14.0	17.0
.9995	5.1	9.6	14.5	19.0	23.5	28.5
.9998	8.2	17.0	25.0	33.0	40.0	48.0
.9999	11.3	22.8	34.0	44.5	54.0	67.0
.99995	14.6	29.5	43.0	57.0	68.0	84.0
.99998	18.8	37.8	56.0	73.0	91.0	112.0
.99999	24.0	44.0	64.0	86.0	110.0	160.0

2) Determine path average rain rates. Each point rain rate resulting from step 1 is converted to a path average rain rate by using linear interpolation to obtain a multiplying factor from the values provided in table 13. These values were taken from curves fitted to data collected in Florida [22].

3) Determine attenuation rate. For each path average rain rate resulting from step 2, an attenuation rate $A_{rr}(q)$ [dB/km] is determined using linear interpolation between the values provided in table 14. These are theoretical values [27] that were determined for a Laws and Parsons [24] drop size distribution.

4) Determine the in-storm ray length. First the length of the direct ray r_{es} that is within T_{es} of the earth's surface is determined using the methods described in 1973 for the calculation

Table 13. Path Average-to-Point Rain Rate Ratio Based on Measurements in Florida [22].

Point Rain Rate in mm/hr	Storm Size Estimated 5 km	10 km	20 km
10	1.0	1.0	1.0
15	0.96	0.916	0.835
18	0.94	0.865	0.73
20	0.93	0.85	0.70
23	0.915	0.83	0.66
27	0.899	0.797	0.61
30	0.888	0.775	0.58
33	0.878	0.755	0.564
37	0.865	0.730	0.54
40	0.860	0.720	0.53
44	0.850	0.704	0.51
50	0.840	0.683	0.493
55	0.833	0.670	0.480
60	0.824	0.650	0.470
65	0.818	0.640	0.452
70	0.813	0.627	0.440
80	0.805	0.610	0.422
90	0.798	0.592	0.408
100	0.790	0.575	0.392
115	0.780	0.565	0.378
140	0.770	0.550	0.357
155	0.765	0.540	0.350
185	0.760	0.528	0.325
200	0.758	0.520	0.310

Table 14. Attenuation in dB/km for Various Rain Rates (assuming Laws and Parsons [24] Drop Size Distribution); Temperature 20°C--after Medhurst [27]

Rainfall Rate		Frequency in GHz											
mm/hr	in/hr	100	60	30	20	15	10	7.5	6	5	4.3	3	2
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.25	0.01	0.25	0.16	0.03	0.01	0.006	0.002	0.0008	0.0004	0.000	0.000	0.000	0.000
1.25	0.05	1.29	0.76	0.21	0.09	0.04	0.01	0.004	0.002	0.001	0.0008	0.0004	0.000
2.5	0.10	2.19	1.43	0.45	0.20	0.10	0.03	0.01	0.005	0.003	0.002	0.0007	0.0003
5	0.20	3.68	2.63	0.93	0.43	0.23	0.07	0.03	0.01	0.006	0.003	0.001	0.0006
12.5	0.49	7.08	5.46	2.43	1.18	0.71	0.24	0.08	0.03	0.02	0.009	0.003	0.001
25	0.98	11.7	9.86	4.87	2.49	1.53	0.60	0.22	0.09	0.04	0.020	0.007	0.002
50	1.97	19.6	17.0	9.59	5.15	3.28	1.45	0.59	0.24	0.10	0.050	0.010	0.005
100	3.94	33.7	29.4	18.4	10.4	6.77	3.43	1.55	0.64	0.26	0.120	0.030	0.010
150	5.91	46.8	40.9	26.8	15.7	10.2	5.49	2.71	1.13	0.47	0.210	0.050	0.020
200	7,87	61.0	56.0	34.0	22.0	14.5	8.10	4.10	1.80	0.73	0.34	0.082	0.036

of $r_{eo,w}$ [17, fig. 21 on p. 72, replace $r_{eo,w}$ with $r_{eo,s,w}$ and $T_{eo,w}$ with $T_{eo,s,w}$]. Here, T_{es} is taken as the storm size; i.e., storm height is assumed to be equivalent to storm diameter [9, p. 98]. Then the final in-storm ray length, r_s, is calculated using

$$r_s[\text{km}] = \left\{ \begin{matrix} T_{es} \text{ if } r_{es} \geq T_{es} \\ \\ r_{es} \text{ otherwise} \end{matrix} \right\} . \tag{33}$$

For transhorizon paths, the storm is assumed to be between the facility and its horizon so that r_{es} is not increased because of ray lengths within T_{es} of the surface that occur beyond the facility horizon.

5) Determine rain attenuation values. Values for the attenuation, $A_r(q)$ for a particular fraction of time are calculated using

$$A_r(q)[\text{dB}] = \left\{ \begin{matrix} 0 \text{ for } q \leq 0.98 \\ A_{rr}(q) r_s \text{ otherwise} \end{matrix} \right\} \tag{34}$$

where $A_{rr}(q)$ values come from step 3 and the value for r_s is from step 4. Note that table 12 yields distributions of rain attenuation that are zero for $q \leq 0.98$.

6) Combine rain attenuation variability with other variabilities. Variability for rain attenuation $Y_r(q)$ is related to the distribution of rain attenuation from (34) by

$$Y_r(q) = -A_r(q) . \tag{35}$$

It is combined with the long-term power fading variability, $Y_e(q)$ [17, sec. A.5], and multipath variability, $Y_\pi(q)$ [17, p. 38], by including $Y_r^{\ 2}(q)$ in an equation of IF-73 [17, (5)]; i.e.,

$$Y_\Sigma(q) = \pm \sqrt{Y_e^2(q) + Y_\Pi^2(q) + Y_r^2(q) + Y_I^2(q)} \text{ dB} \quad (36)$$

+ for $q \leq 0.5$

- otherwise

where $Y_\Sigma(q)$ is the total variability and $Y_I(q)$ is a variability included in IF-77 to allow for ionospheric scintillation (sec. 4.5).

4.5 Ionospheric Scintillation

Variability associated with ionospheric scintillation [1; 46] for paths that pass through the ionosphere (i.e., on earth/satellite paths) at an altitude of about 350 km [32, p. 4] is included in IF-77. This variability, $Y_I(q)$ dB, is determined using figure 7 [46; 47, fig. 6] directly if calculations are to be for a specific scintillation index group (see fig. 7 inset) or using a weighted mixture of the figure 7 distributions (sec. 4.1) where the weighting factors are estimated for specific problems. For example, a computer program available at NTIA/ITS [33] that is an extension of the Fremouw model [13] can be used to estimate weighting factors for frequencies up to 400 MHz [32]. An equation given previously in section 4.4, (36), is used to add $Y_I(q)$ to IF-77.

Provisions exist (table 2, index group 6) to allow $Y_I(q)$ to change with earth facility latitude when a geostationary satellite is involved and the earth facility locations are along the subsatellite meridian. Figure 8 shows the distributions currently used when this option is selected. These distributions were developed by mixing distributions for particular scintillation index groups in accordance with the estimated time for which they would be present at a frequency of 136 MHz so that the frequency scaling factor discussed below should be used with these distributions [43, table 5]. However, only minor program modifications would be necessary to incorporate other distributions that might be of interest.

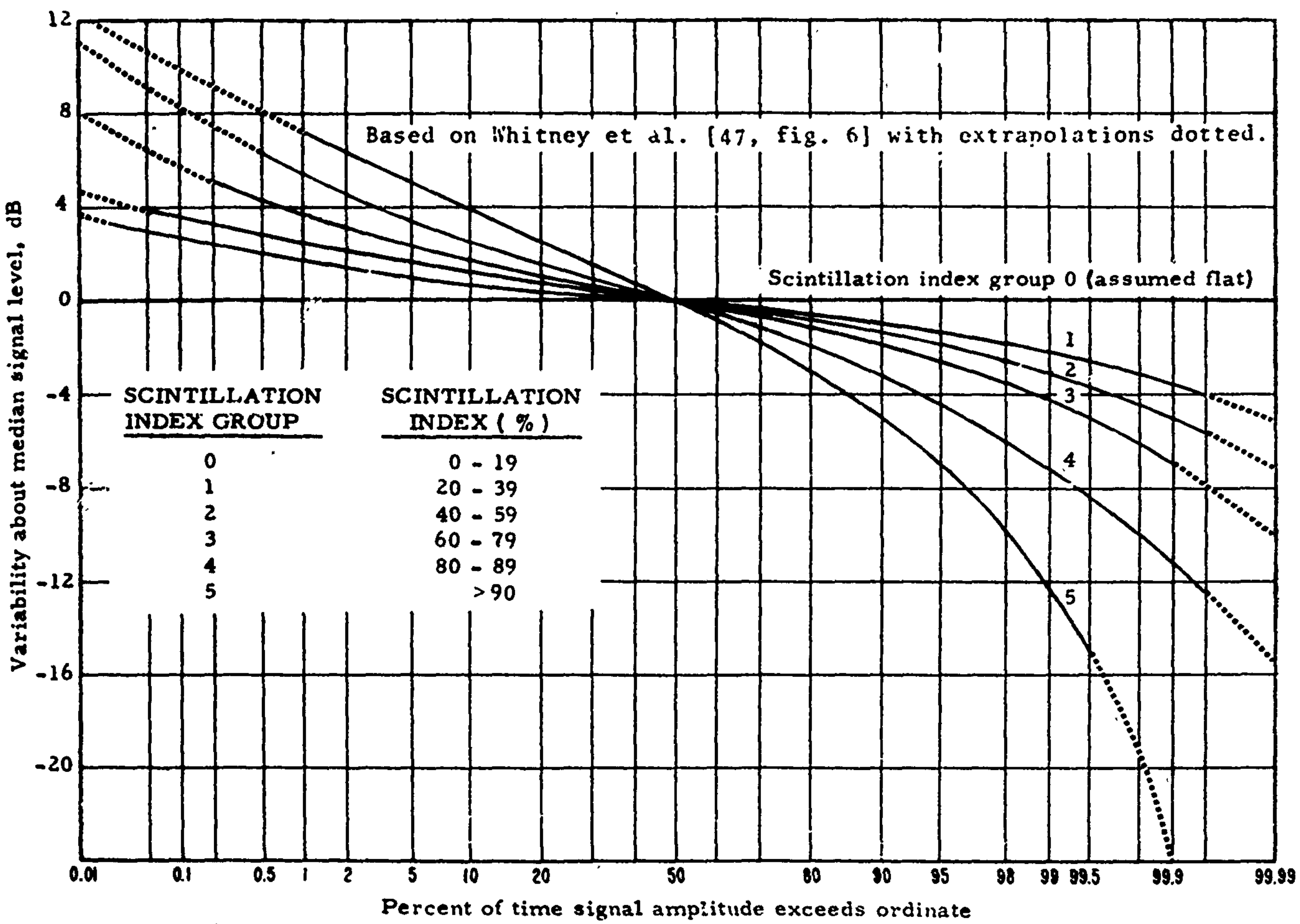

Figure 7. Signal-level distributions for ionospheric scintillation index groups. The scintillation index or SI used here may be taken as the ratio of the peak excursion from the mean power level to the mean power level [33, p. 4].

When the distributions of figure 8 are used for a frequency other than 136 MHz, an optional frequency scaling factor should be used. It relates $Y_I(q)$ to $Y_{136}(q)$ from figure 8 by

$$Y_I(q) = (136/f)^n \, Y_{136}(q) \tag{37}$$

where n varies with earth facility latitude, θ_{FL} [43, (27)]; i.e.,

$$n = \begin{cases} 1 \text{ for } \theta_{FL} \le 17° \text{ or } \theta_{FL} \ge 52° \\ 1 + (\theta_{FL} - 17)/7 \text{ for } 17° < \theta_{FL} < 24° \\ 2 \text{ for } 24° < \theta_{FL} < 45° \\ 1 + (52 - \theta_{FL})/7 \text{ for } 45° < \theta_{FL} < 52. \end{cases} \tag{38}$$

Other scaling factors could be used with minor program modifications.

5. TROPOSPHERIC SCATTER

The Rice et al. [36, sec. 9] method, which is used to calculate attenuation for tropospheric scatter in IF-73 [17, sec. A.4.4], is not applicable to paths that involve a very high antenna such as a satellite. This method was reformulated by Dr. George A. Hufford (DOC-BL, informal communication) to include geometric parameters associated with very high antennas where these parameters are determined using ray tracing techniques. The resulting formulation has been incorporated into IF-77 and is presented here. It was developed using kilometers as a measure of length so that all lengths in the formulas of this section are in kilometers.

Frequency and the basic geometric configuration for the tropospheric scatter path are assumed to be known so that values for the following parameters are available where

$h_{1,2}$ [km-msl] = antenna elevations above mean sea level (msl),

h_{rs} [km-msl] = effective reflecting surface elevation above msl,

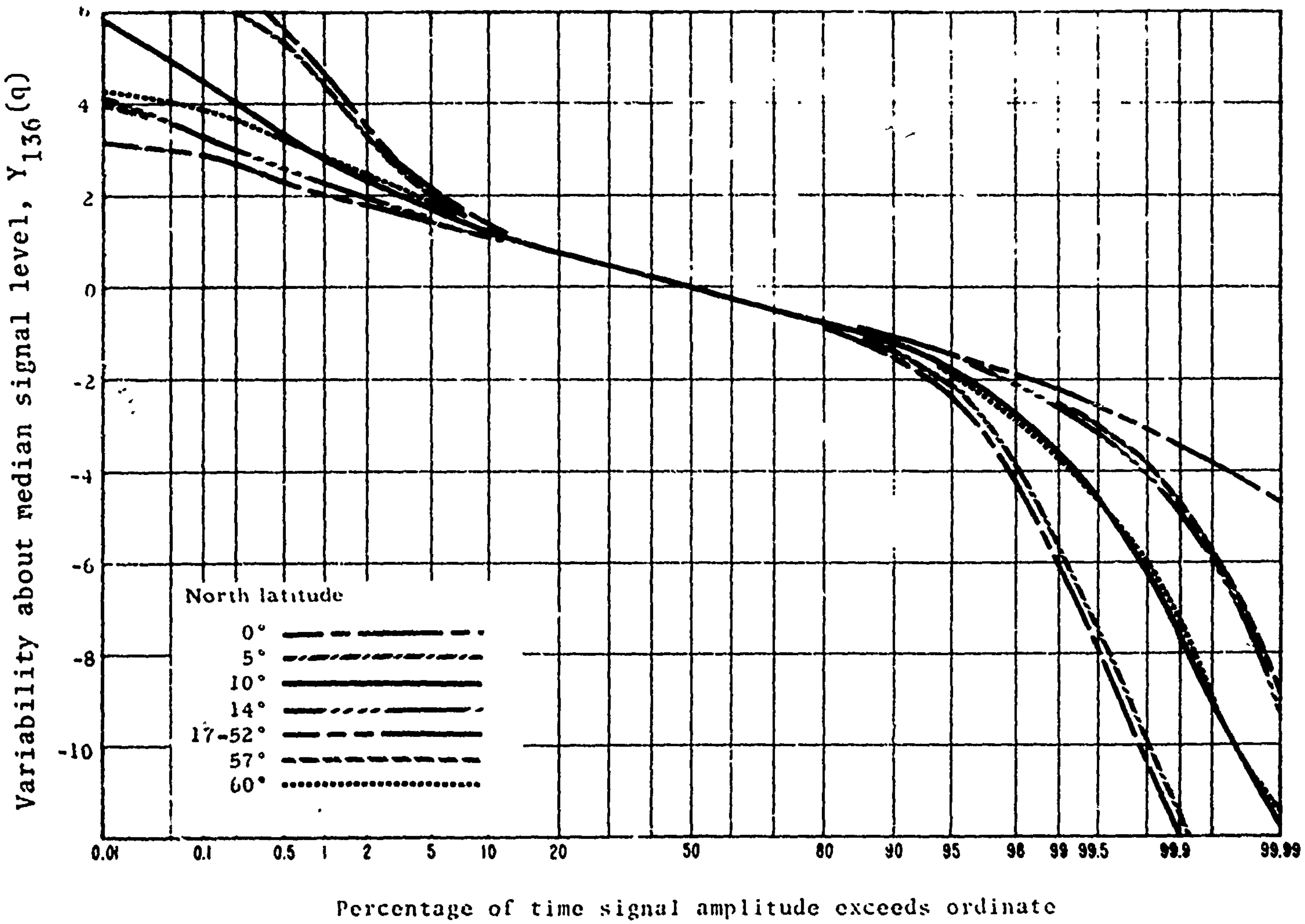

Figure 8. Signal-level distributions currently used with variable scintillation group option selected. These distributions were developed from data collected at 136 MHz [43, sec. 3.4] so that the frequency scaling factor should be used with them.

where h_{rs} is also taken as average terrain elevation,

h_v [km-hrs] = common volume elevation above h_{rs},

$\ell_{1,2}$[km] = antenna to common volume ray lengths,

N_s [N-units] = surface refractivity at h_{rs},

Θ[rad] = scattering angle,

and

λ[km] = wavelength.

The scattering efficiency term, S_e, is calculated as follows:

$$\varepsilon_1 = 0.031-2.32(10^{-3})N_s+5.67(10^{-6})N_s^2, \tag{39}$$

$$\gamma = 0.1424\{1+\varepsilon_1\exp[-(0.25h_v)^6]\}, \tag{40}$$

$$\varepsilon_2 = 0.002N_s^2-0.06N_s+6.6, \tag{41}$$

and

$$S_e = 91.1 - \frac{\varepsilon_2}{1+0.7716h_v^2} +20\log[(0.1424/\gamma)^2\exp(\gamma h_v)]. \tag{42}$$

The scattering volume term, S_v, is calculated as follows:

$$s = \frac{\ell_1-\ell_2}{\ell_1+\ell_2} \tag{43}$$

where s is the modules of asymmetry,

$$A = (1-s^2)^2, \tag{44}$$

$$\ell = \ell_1+\ell_2 \tag{45}$$

where ℓ is the total ray length,

$$\eta = \gamma\Theta\ell/2, \tag{46}$$

$$\chi_1 = (1+s)^2\eta, \tag{47}$$

$$\chi_2 = (1-s)^2\eta, \tag{48}$$

$$\kappa = 2\pi/\lambda \tag{49}$$

where κ is the wave number,

$$\rho_{1,2} = 2\kappa\Theta(h_{1,2}-h_{rs}), \tag{50}$$

$$q_{1,2} = (\chi_{1,2}+\sqrt{6})^2+\rho_{1,2}^2, \tag{51}$$

$$
\begin{aligned}
B = {} & 6 + 8s^2 \\
& +8(1+s)^2 x_2^2 \rho_2^2/q_2^2, \\
& +8(1-s)^2 x_1^2 \rho_1^2/q_1^2 \\
& +2(1-s)^2 (1+2x_1^2/q_1)(1+2x_2^2/q_2),
\end{aligned}
\tag{52}
$$

$$
C = 12\left(\frac{\rho_1+\sqrt{2}}{\rho_1}\right)^2 \left(\frac{\rho_2+\sqrt{2}}{\rho_2}\right)^2 \frac{\rho_1+\rho_2}{\rho_1+\rho_2+2\sqrt{2}}
\tag{53}
$$

and

$$
S_v = 10 \log\left[(An^2+Bn)\frac{q_1 q_2}{\rho_1^2 \rho_2^2} + C\right] .
\tag{54}
$$

Finally, the attenuation for scatter, A_s, relative to free space is calculated using

$$
A_s[\mathrm{dB}] = S_e + S_v + 10 \log \frac{\theta^3}{\lambda \ell} .
\tag{55}
$$

6. CONDITIONAL ADJUSTMENT FACTOR

The conditional adjustment factor, A_Y, is used in IF-73 to prevent available signal powers from exceeding levels expected for free-space propagation by unrealistic amounts when the variability is large and the calculated reference level is near its free-space value. This is accomplished by adding A_Y to calculated reference basic transmission loss, L_{br}, in the computation of median basic transmission loss, L_b (0.5) [17, pp. 40, 41]. However, the resulting increase in transmission loss can be too large for frequencies near 400 MHz when climates or time blocks with large variabilities are used. For example, the use of Time Block 7 (sec. 4.2) can result in an A_Y of 20 dB.

To prevent excessive loss increases associated with A_Y, a formulation to keep $A_Y \leq 10$ dB has been incorporated into IF-77. This formulation may be summarized as follows:

$f_{\theta h}$ = elevation angle correction factor [17, (179)],

L_{bf} = basic transmission loss for free space [17, (15)],

L_{br} = basic transmission loss calculated reference level [17, (17)],

Y_T = a parameter from IF-73 [17, (182)],

$Y(q)$ = a long-term variability parameter which is calculated using (31) and (32) with c values from tables 10 and 11,

$$Y_{eI}(q) = f_{\Theta h}\, Y(q), \tag{56}$$

$$A_{YI} = \begin{cases} 0 \text{ if lobing option [17, sec. 3.1.1] is used and the aircraft is within 10 lobes of its radio horizon} \\ (L_{bf} - 3) - [L_{br} - Y_{eI}(0.1] \text{ otherwise} \end{cases}, \tag{57}$$

$$A_Y = \begin{cases} 0 \text{ if } A_{YI} \le 0 \\ 10 \text{ if } A_{YI} \ge 10 \\ A_{YI} \text{ otherwise} \end{cases}, \tag{58}$$

$$Y_e(q<0.1) = \begin{cases} \text{lesser of } \begin{Bmatrix} Y_{eI}(q) \\ \text{or} \\ Y_T \end{Bmatrix} \text{ for lobing} \\ \text{lesser of } \begin{Bmatrix} Y_{eI}(q) \\ \text{or} \\ L_{br} + A_Y - (L_{bf} - c_Y) \end{Bmatrix} \text{ otherwise}. \end{cases} \tag{59}$$

Where c_Y is 6, 5.8, and 5 dB for q values of 0.001, 0.001, and 0.01 respectively,

$$Y_e(q=0.1) = \begin{cases} L_{br} - L_{bf} + 10 \text{ if } A_Y \ge 10 \\ Y_{eI}\ (0.1) \text{ otherwise} \end{cases}$$

and

$$Y_e(q > 0.1) = Y_{eI}(q). \tag{60}$$

These equations replace similar equations in IF-73 [17, sec. A.5].

7. TRANSITION DISTANCE

The transition distance d_o is used in blending attenuation, valid within line-of-sight, with the radio horizon value. It is the largest distance in the line-of-sight region at which

diffraction effects associated with terrain are considered negligible. Values estimated for d_o in IF-73 [17, (140)] have been found to be too small when low antennas are used for both antennas. To correct this difficulty, d_o estimates in IF-77 are made using

$$d_o = \begin{bmatrix} d_{L1} \text{ when } d_{L1} > d_d \\ d_{\lambda/6} \text{ when } d_{\lambda/6} > d_{L1} \text{ and } d_d \\ d_d \quad \text{otherwise} \end{bmatrix} \tag{61}$$

where d_{L1} is the horizon distance for the lower terminal (sec. 9.2), $d_{\lambda/6}$ is the distance at which the path length difference, Δr [17, (56)], is equal to $\lambda/6$ (λ is wave length), and d_d is the d_o of IF-73 [17, (140)]. The distance $d_{\lambda/6}$ is the largest distance at which a free-space value is obtained in a two ray model of reflection from a smooth earth with a reflection coefficient of -1.

8. FREE SPACE LOSS

The ray length, r, term of the free-space loss portion of IF-73 [17, (15)] when computed via the IF-73 formulation [17, r_o from (54) for line-of-sight or path distance d for trans-horizon paths] can give loss values that are much too low when a very high (satellite) antenna is involved. To extend IF-73 to such cases in IF-77, a new formualtion for r was developed.

This formulation may be summarized as follows:

a_o = actual earth radius (6370 km = 3440 n mi),

d = great-circle path distance,

$d_{L1,2}$ = horizon distances,

$h_{L1,2}$ = horizon elevations (above msl) from (72) and IF-73 (see eqn. 396 of App. A).

$h_{1,2}$ = antenna elevations (above msl),

r_o = length of direct ray in IF-73 [17, (54)],

$$r_{WH}^2 = (h_2-h_1)^2+4(h_1+a_o)(h_2+a_o)[\sin(0.5d/a_o)]^2, \tag{62}$$

where r_{WH} is the within-the-horizon ray length between antennas above an air-less earth (i.e., bending neglected),

$$r^2_{L1,2} = (h_{1,2}-h_{L1,2})^2 + 4(h_{1,2}+a_o)(h_{L1,2}+a_o)[\sin(0.5d_{L1,2}/a_o)]^2 \quad (63)$$

where $r_{L1,2}$ are antenna to horizon ray length for an airless earth (no ray bending),

$$D_s = (d-d_{L1}-d_{L2}) \quad (64)$$

where D_s is the distance between horizons,

$$r_{BH} = r_{L1}+r_{L2}+D_s \quad (65)$$

where r_{BH} is the total ray length for a beyond-the-horizon path, and

$$r = \text{greater of} \begin{Bmatrix} r_o \text{ or } r_{WH} \text{ for within-the-horizon} \\ \text{or} \\ d \text{ or } r_{BH} \text{ for beyond-the-horizon} \end{Bmatrix}. \quad (66)$$

Equations (62) and (63) are simply the application of the half-angle law of cosines formulation where two sides (a_o + elevation) and an included angle (great-circle distance $/a_o$) are known.

9. AIRBORNE FACILITY

The IF-77 version allows the facility (or lower) antenna to be airborne; i.e., IF-73 was extended to cover air/air and air/satellite cases. This extension involves the more extensive use of parameters based on ray tracing in parts of the model associated with the facility antenna. For the most part, these parameters are similar to those used in IF-73 for the aircraft antenna only.

9.1 Smooth Earth Horizons

Ray tracing is now used to determine the smooth earth horizon distances associated with both terminals, $d_{Lo1,2}$, that are used in the calculations associated with long-term power fading [17, sec. A.5]. These distances are determined by ray tracing from the earth's surface to the respective antenna heights where the initial take-off angle is 0° and the surface refractivity

($N_s = 329$ N-units) corresponds to a 9000 km (4860 n mi) effective earth radius.

The IF-77 version uses ray tracing to determine smooth earth horizon distances associated with both terminals, $d_{Ls1,2}$, that are used in the calculation of effective antenna heights. These distances are determined by ray tracing from the reflecting surface elevation [17, fig. 13] of the earth's surface to the respective antenna heights. The initial take-off angle used is 0° and the surface refractivity, N_s, is calcualted from the N_o or effective earth value specified for the path [17, (18), (20)]. Values for $d_{Ls1,2}$ are used to determine effective antenna heights, $h_{e1,2}$, and effective heights above reflecting plane, $H_{1,2}$, as follows:

a = effective earth radius [17, 20].

a_a = adjusted earth radius [17, (44)],

a_o = actual earth radius (6370 km = 3440 n mi),

$h_{a1,2}$ = actual antenna elevations above reflecting surface elevation

h_{cg} = height of facility counterpoise above ground at the facility site,

h_{fc} = height of the facility antenna above its counterpoise,

$$\theta_{s1,2}\ [\text{rad}] = d_{Ls1,2}/a \tag{67}$$

$$h_{e1,2} = \text{lesser of} \begin{bmatrix} h_{a1,2} \\ \text{or} \\ \begin{Bmatrix} 0.5\, d^2_{Ls1,2}/a \text{ if } \theta_{s1,2} \leq 0.1 \text{ rad} \\ a[\sec(\theta_{s1,2})-1] \text{ otherwise} \end{Bmatrix} \end{bmatrix}, \tag{68}$$

$$\Delta h_{e1,2} = h_{a1,2} - h_{e1,2}, \tag{69}$$

$$\Delta h_{a1,2} = \Delta h_{e1,2}(a_a - a_o)/(a - a_o), \tag{70}$$

$$H_1 = \begin{Bmatrix} h_{a1} - \Delta h_{a1} \text{ for ground reflection} \\ h_{fc} \text{ for counterpoise reflection} \end{Bmatrix}, \tag{71}$$

and

$$H_2 = \begin{Bmatrix} h_{a2}-\Delta h_{a2} \text{ for ground reflection} \\ h_{a2}-\Delta h_{a2}-h_{cg} \text{ for counterpoise reflection} \end{Bmatrix} . \qquad (72)$$

These expressions are extensions of similar ones used in IF-73 [17; (34), (32), (45), (46), (48), (49)].

9.2 Facility Horizon

The IF-73 version allows the facility horizon to be specified by (a) any two horizon parameters (elevation, elevation angle, or distance), (b) estimated with any one horizon parameter and the terrain parameter, Δh, (c) estimated from Δh alone, or (d) calculated for smooth earth conditions [17, fig. 14]. Some of this flexibility must be sacrificed when the facility is high since the accurate specification of more than one horizon parameter requires prior knowledge of ray tracing results.

The IF-77 version was constructed to retain all facility horizon specification flexibility for low facility antennas and yet allow ray tracing to be used for high facility antennas. This method may be summarized as follows:

1) Determine horizon parameters as they were determined in IF-73 [17, fig. 14], but consider the results as initial values that may be changed if the facility antenna is too high. The resulting parameters are

   θ_{Ie1} = initial estimate of the horizon elevation angle θ_{e1},

   h_{IL1} = initial estimate of the facility horizon elevation h_{L1}, and

   d_{IL1} = initial estimate of facility horizon distance d_{L1}.

2) Facility antenna height, h_1, and effective antenna height, h_{e1}, from (68) are used to test the initial

horizon parameters and the initial parameter values are replaced by ones appropriate for a smooth earth if the test conditions are met; i.e., smooth earth values are used if

$$h_{e1} > 3 \text{ and } \begin{Bmatrix} \theta_{Ie1}>0 \text{ and } h_1>h_{IL1} \\ \text{or} \\ \theta_{Ie1}\leq 0 \text{ and } h_1<h_{IL1} \end{Bmatrix} .$$

3) This step is not used if smooth earth parameters were selected in step 2. If Δh_{e1} from (69) is zero or less the initial horizon parameter values from step 1 are used, otherwise ray tracing is used to determine values for θ_{e1} and d_{L1}; i.e.,

$$h_{L1} = h_{IL1} \tag{73}$$

$$\theta_{e1} = \begin{Bmatrix} \theta_{Ie1} \text{ if } \Delta h_{e1}\leq 0 \\ \text{otherwise use ray tracing} \end{Bmatrix} \tag{74}$$

and

$$d_{L1} = \begin{Bmatrix} d_{IL1} \text{ if } \Delta h_{e1}\leq 0 \\ \text{otherwise use ray tracing} \end{Bmatrix} . \tag{75}$$

The ray tracing referred to in the equations above is started at the horizon elevation, h_{L1}, with a take-off angle of $-\theta_L$ and continues until the facility antenna height h_1 is reached. Then the great-circle distance traversed by the ray is taken as d_{L1}, and the negative of the ray arrival angle is taken as θ_{e1}. The take-off angle used is calculated from

$$-\theta_L = -(\theta_{Ie1}+d_{L1I}/a). \tag{76}$$

10. ANTENNA PATTERNS

This section deals with the use of vertical plane antenna patterns in IF-77. These patterns give gain relative to the main beam gain in the vertical plane [17, sec. A.4.2; 21, figs. 45 and 46]. Azimuth patterns are used only in program TWIRL

(table 1) which is described in the APPLICATIONS GUIDE [21, sec. 3], but these patterns are considered to be more a part of that particular program than part of the propagation model and are not discussed here.

10.1 Aircraft Antenna

The aircraft (or higher terminal) antenna pattern in IF-73 was taken as isotropic, and modifications to allow for aircraft antenna pattern effects are included in IF-77. This extension involves the use of the gain factors which are discussed in section 3.4.

Aircraft antenna pattern options currently built into the IF-77 include an isotropic antenna and a JTAC [21, (11)] directional pattern where the half-power beamwidth and the tilt of the antenna is an input in degrees. Program modifications can easily be made to accommodate other patterns that are specified in terms of gain versus elevation angle. Horizontal (or azimuth) patterns for the aircraft antenna are not used in any of the programs.

Antenna pattern data as used in IF-77 is normalized to the main beam gain. The extent to which the main beam antenna gain exceeds that of an isotropic antenna is considered as a separate item for the receiving antenna and is included in the specification of Equivalent Isotropically Radiated Power for the transmitting antenna (EIRP); i.e.,

$$\text{EIRP [dBW]} = P_{TR}\text{[dBW]} + G_T\text{[dBi]} \tag{77}$$

where P_{TR} is the total power radiated from the antenna and G_T is the main beam gain of the transmitting antenna relative to isotropic.

10.2 Ray Elevation Angles

Incorporation of an aircraft antenna pattern into the model via antenna gain factors (sec. 3.4) requires that gain values be obtained from the pattern for the direct and reflected rays at appropriate elevation angles. In terms of the variables that are similar to those of IF-73 [17, sec. A.4.2], direct ray

elevation angles $\Theta_{H1,2}$ and ground reflected rays $\Theta_{g1,2}$ are given by

$$\Theta_{h1,2} = \pm\alpha - \Theta_{1,2} \text{ (use + for } \Theta_{h1}\text{)}, \tag{78}$$

$$\Theta_{H1,2} = \Theta_{h1,2} + \Theta_{L1,2}, \tag{79}$$

$$\Theta_{g1,2} = \Theta_{L1,2} - \Psi - \Theta_{1,2}, \tag{80}$$

where $\Theta_{L1,2}$ is a smooth horizon elevation angle adjustment term, and the remaining parameters are calculated as in IF-73; i.e., α [17, (53)], $\Theta_{1,2}$ [17, (50)], and ψ [77, fig. 19]. Values for $\Theta_{L1,2}$ are obtained from

$$\Theta_{L1,2} = \left(\Theta_{LR1,2} - \Theta_{LE1,2}\right)\left(\frac{a_a - a_o}{a - a_o}\right) \tag{81}$$

where $\Theta_{LR1,2}$ are the elevation angles of the smooth earth horizon rays as determined with ray tracing, $\Theta_{LE1,2}$ are the elevation angles of the horizon rays as determined using the effective earth model, and the remaining parameters are calculated as in IF-73; i.e., a_a [17, (44)], a_o [17, (19)], and a [17, (20)]. Values for $\Theta_{LE1,2}$ are obtained from

$$\Theta_{LE1,2} = \text{Cos}^{-1}(a/(H_{1,2}+a)) \tag{82}$$

where a[17,(20)] and $H_{1,2}$ [17,(47)(48)] are the effective earth radius and antenna heights of IF-73. The effect of $\Theta_{L1,2}$ is to force $\Theta_{H1,2}$ and $\Theta_{g1,2}$ to have the values obtained via ray tracing at the smooth earth radio horizon, and prorate values obtained elsewhere. The prorating factor $(a_a-a_o)/(a-a_o)$ used here is the same factor used to adjust Δh_e [17, (46)] in IF-73.

10.3 Tracking Options

Tracking options are available for each terminal. When a tracking option is used for a terminal, its antenna's main beam is always pointed at the antenna of the other terminal or at the radio horizon when the path is a transhorizon path. This is accomplished by setting the beam tilt of the antenna that is tracking to the direct ray elevation angle where this angle

becomes the horizon elevation angle for transhorizon paths. For example, when the tracking option is used for both antennas the full gain of both antennas will be included in the calculation of transmission loss for free-space conditions.

10.4 TACAN Vertical Pattern

The TACAN RTA-2 vertical pattern used with IF-77 [21, fig. 45] is based on a statistical analysis of International Telephone and Telegraph (ITT) production test data for 23 antennas. Each of these antennas were tested at 3 or more frequencies so that a total of 78 patterns were used. Of these, 37 were low band (below 1088 MHz) and 41 were high band (above 1087 MHz). Gain values at 3° intervals for elevation angles from -60° through 60° were used to obtain a distribution of gain at each elevation angle. Gain values exceeded at each angle for 5, 50, and 95 percent of the data are shown on figure 9 along with the standard deviation of the gain measurements. Also shown in figure 9 are gain measurements for a single antenna in the above 60° and below -60° range that were obtained from a military report with limited distribution, and the piecewise linear approximation used for the 50 percent in IF-77.

11. SUMMARY

This report covers extensions that were made to IF-73 [17] in the process of developing the 1977 capabilities [21] of table 1. These extensions allow the programs to be used for a wider variety of problems such as those involving air/air or air/satellite propagation. A brief description of the propagation model provided in section 2 is followed by detailed discussions of specific model extensions. Minor changes to and errata for IF-73 are provided in Appendix A.

The 1977 propagation model (IF-77) has been incorporated into computer programs that are useful in estimating the service coverage of radio systems operating in the frequency band from 0.1 to 20 GHz. They may be used to obtain a wide variety of computer-generated microfilm plots. A plotting capability summary is

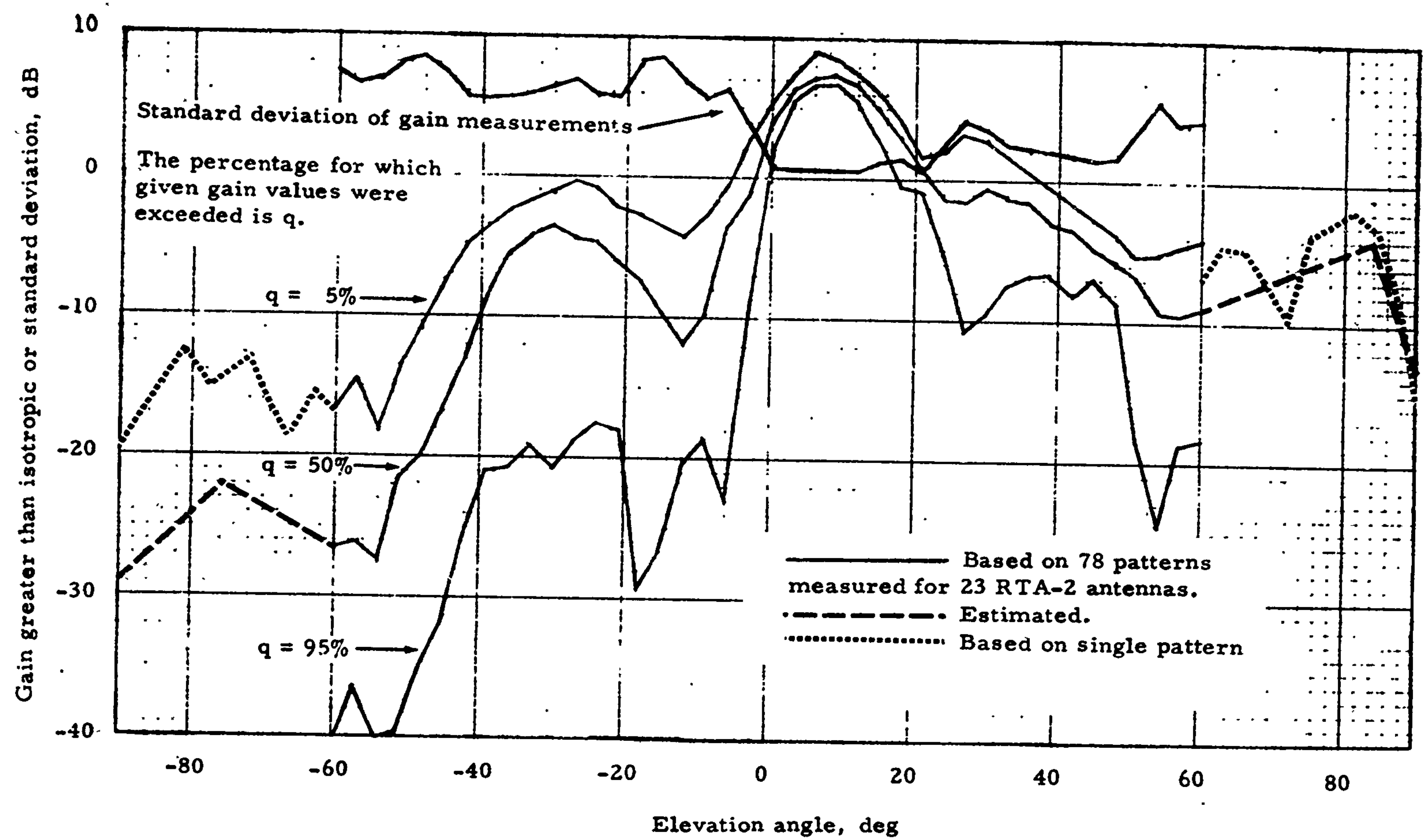

Figure 9. Antenna gain statistics for TACAN RTA-2

provided in table 1 and program input parameters are summarized in tables 2 through 4. These tables were taken from an APPLICATIONS GUIDE [21] for the programs where these capabilities and parameters are discussed in detail.

Potential users should 1) read the brief description of the propagation model provided in section 2 to see if the model is applicable to his problem, 2) select the program(s) whose output(s) are most appropriate from the information given in table 1 [21, sec. 3], 3) determine values for the input parameters given in tables 2 through 4 [21, sec. 4], 4) request a cost estimate for appropriate computer runs, and 5) submit the formal request and/or purchase order that may be required.

Requests to the FAA should be addressed to:

Federal Aviation Administration
Systems Research and Development Service
Spectrum Management Staff, ARD-60
2100 Second Street, S.W.
Washington, D. C. 20591

Attention: Navigation Specialist

Telephone contact is strongly encouraged, and Mr. Robert Smith can be reached at 426-3600 if the Federal Telecommunications System (FTS) is used, or (202) 426-3600 if commercial telephone is used.

Other requests should be addressed to:

Department of Commerce
Spectrum Utilization Division, NTIA/ITS-1
325 Broadway
Boulder, CO 80303

Attention: Mary Ellen Johnson

Telephone contact is strongly encouraged, and Mrs. Johnson can be reached at 323-3587 if FTS is used or (303) 499-1000 x 3587 if commercial telephone is used. If extension 3587 can't be reached, try extension 4162, which is the Spectrum Utilization Division Office.

12. ACKNOWLEDGMENTS

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APPENDIX A. CHANGES FOR FAA-RD-73-103

Computer Programs for Air/Ground Propagation and Interference Analysis 0.1 to 20 GHz

G. D. Gierhart and M. E. Johnson

September 1973*

All changes (errata and minor modifications) recommended for the above report by the authors as of May 1978 are listed below. These changes do not include modifications associated with the 1977 extensions that are discussed in the text of the present report, but do include some minor modifications that were made to accommodate the extensions. Readers finding additional errata are urged to contact an author at the U. S. Department of Commerce; Spectrum Utilization Division, NTIA/ITS-1, Boulder, Colorado 80303. Mrs. Johnson can be reached via commercial telephone at (303) 499-1000 x 3587 or on the Federal Telecommunications System (FTS) at 323-3587. The changes are:

Page	Location	Changes
5	End of first paragraph . . .	Change the (fig. 3) to (fig. 5).
15	Line 2	Change the Ns to N_s.
39	Line 1	Change "...S_a(q) available for a fraction of the time > q ..." to "...S_a(q) exceeded for a fraction of the time q ...".

*This DOT report is now available from the National Technical Information Service, Operations Division, Springfield, VA 22151. Order using accession number AD 770 335.

Page	Location	Changes
39	(8)	Change the 50 to 0.5.
41	(16)	Change"...if lobing..." to "...or if lobing..." and delete "or path is beyond line of sight".
	End of first paragraph . . .	Change the (3) to (5).
48	After (39)	Insert: The aircraft horizon height H_{L2} km-msl, is calculated from

$$D_S = d - d_{L1} - d_{L2} \text{km} \tag{39a}$$

and

$$h_{L2} = \begin{Bmatrix} h_{L1} \text{ if } D_S \leq 0 \\ h_{rs} \text{ otherwise} \end{Bmatrix} \text{km.} \tag{39b}$$

Page	Location	Changes
51	(45)	Change the Δh_a to Δh_e.
52	(58)	Change the $\psi + \theta$ to $-(\psi + \theta_1)$.
53	(68) and (69) . .	Change the $\phi_{h,v}$ to ϕ.
54	(77)	Change the V_g to V_c.
56	(78)	Change right-hand side to

$$\begin{Bmatrix} R_g \text{ if } d_c \leq 0 \\ f_g\ R_g \text{ otherwise} \end{Bmatrix}.$$

Page	Location	Changes
57	(81)	Change the $= R_{Tg}$ to $+ F_{fs}\ R_{Tg}$.
	After (81)	Insert: Where

$$F_{fs} = \begin{Bmatrix} 1 \text{ if lobing option (sec. 3.1) is used} \\ 1 \text{ if } \Delta_{rg} \leq 0.5\ \lambda \text{ and } |g_D + R_{TG} \exp(-j\ \phi_{TG})| < g_D \end{Bmatrix} \tag{81a}$$

0 otherwise. .

Page	Location	Changes
59	(86)	Change to $d_3 = d_{PL} + 0.5\ (a^2/f)^{1/3}$ km.

Page	Location	Changes
60	(90)	Change to $\Theta_3 = 0.5(a^2/f)^{1/3}/a$ rad (90a) $\Theta_4 = 1.5(a^2/f)^{1/3}/a$ rad (90b)
62	Fig. 20 caption .	Change the last h_{ee1} to h_{ee2}.
	(108)	Change the d_{K1} to d_{KL1}.
63	(118)	Change the sign of $\frac{h_{ee1,2}}{d_{eL1,2}}$ to minus.
64	(121)	Change the 2.583 sin (θ_v) to 5.1658 sin $(0.5\ \theta_v)$.
65	(126)	Change the right hand side to $2\ \mathrm{Sin}^{-1}\left[\left(\frac{0.5}{5.1658}\right)\sqrt{d_{ML}/\left(fd_{L1}d_{KL2}\right)}\right]$.
	(128)	Change the right hand side to $-a\ \tan(\Theta_5) + \sqrt{(a\ \tan\ \Theta_5)^2 + 2a(h_{L1} - h_{s2})}$
	Line following (128)	Insert "h_{s2} is from (130)" between "," and "and."
	(133)	Change the 2.583 sin (θ_6) to 5.1658 sin $(0.5\ \theta_6)$.
66	(134)	Change the 20 to -20.
	(135)	Insert "1" between "$\}$ " and "+".
	Second line after (135) .	Change "... e path..." to "...K path...".
70	(163)	Change the right hand side to $0.5696\ h_o \left\{1 + \eta\ \exp\left[-3.8\ (0.1\ h_o)^6\right]\right\}$.
75	(182)	Change the right hand side to $L_b(0.5) - [L_{bf} - V_e(0.5, d_e) - 20\ \log(R_{TG} + R_{TC})]$

Page	Location	Changes
76	Line 2	Change the (15) to (16).
	(184)	Change the $L_b(0.5)$ to $L_{br} + A_y$.
78	Line 5	Change "$F_{\sigma h}$ from (66)" to "$\sigma_h \sin(\psi)/\lambda = \delta$".
	(194)	Change the right hand side to $0.01 + 946\ \delta^2$ if $\delta < 0.00325$ $6.15\ \delta$ if $0.00325 \leq \delta \leq 0.0739$ $0.45 + \sqrt{0.000843 - (\delta - 0.1026^2}$ if $0.0739 < \delta < 0.1237$ $0.601 - 1.06\ \delta$ if $0.1237 \leq \delta \leq 0.3$ $0.01 + 0.875 \exp(-3.88\delta)$ otherwise
	(196)	Change the $R_s^2 + R_d^2$ to $\dfrac{R_s^2 + R_d^2}{g_D^2}$
	First line after (196) .	Insert ", g_D is as defined for (81)." between "(40)" and "and d".
86	From bottom lines 3 & 4 .	Change text for codes (0) and (3) to: "(0) no parameters specified" and "(3) both the angle and the elevation are specified".
87	.	Change "dB-W/sq mi" in text for PMIN, PMAX, and YC to "dB-W/sq m".
104	4th line after statement 22	Change the U50 to D50.
	3rd line after statement 25 . .	In READ 7 "HPRI" should be "HPFI" and "ISC" should be "KE".
108	Statement 8 . . .	Change the I2 to 2I2.
111	Line 5	Change "Read 8...IA" to "Read 8...IA, JJ".

Page	Location	Changes
114	From page bottom lines 7 & 8 . . .	Change KE's in the two statements preceding statement 73 (near page bottom) to JE's.
120 128 135	Immediately after first comment statement.	Replace the whole line with LE = 11.
124 131 138	After statement 136.	Insert "IF(SI.LE.SILIM.AND.ILB.LE.0.) GO TO 137". Attach statement numbers "138" and "139" to the next two lines then skip a line and replace the next line with "IF(DZR.LT.0.) GO TO 145".
125 132 139	Statement 46 . . .	Replace with "46 RST=((RGP*RSP+RDG*RDG)/(GOD*GOD))+WA".
125 133 139	Statement after statement 22 .	Replace with "TLIM=+20.*ALOG10(GOD+REG+REC)-GPD+(AD(18)*FTH)".
125 133 140	After statement 135 insert	"137 WRL=CABS(GOD+AT2) IF(WRL.LE.GOD) GO TO 138 WRL=CABS(GOD+AT1) WR=WRL*WRL+(.0001*GOD)$GO TO 139.
125 133 140	Right before statement 148 .	Insert 145 DZR = 0.
142	Line 7	Replace ".193573364" with ".09679".
	Line before statement 30 . . .	Delete
	Two lines after statement 30 . . .	Replace with "TX=((A*A/F)**THIRD)/A T3=0.5*TX $ 1.5*TX".
143	3rd line past statement 45 . . .	Replace with "TH=2.*ASINF(CU*SQRTF(D/F*DL1*DL2)))".
	9th line after statement 45 . .	Replace "V5..." with "V5=5.1658*SINF(0.5*TH5)*TM5".
144	Line 6	Change the DLK4 to D4.

Page	Location	Changes
144	Line 11	Replace "V4=..." with V4=5.1657(SINF(0.5*TH)*TM2)."
146	Statement 24 . .	The symbol after CALB should be a "+".
178		Replace "PSWRB" in title and first line with "PWSRB".
187	Statement 24 . .	Insert a "+" just after THET.

APPENDIX B. LIST OF SYMBOLS

This list includes most of the abbreviations, acronyms, and symbols used in this report except for those used only in Appendix A. Many are similar to those previously used in other reports [17, 18, 21, 26, 35, 44]. The units given for symbols in this list are those required by or resulting from equations as given in this report. Except where otherwise indicated, equations are dimensionally consistent so that appropriate units can be selected by the user.

In the following list, the English alphabet precedes the Greek alphabet, letters precede numbers, and lower-case letters precede upper-case letters. Miscellaneous symbols and notations are given after the alphabetical items.

a	Effective earth radius as calculated in IF-73 [17, (20)].
app.	Appendix.
a_a	An adjusted effective earth radius shown in figure 2 [17, (44)].
$a_{n,p}$	Principal radii of curvature of reflecting surface of the reflecting point and within, a_p, or normal, a_n, to the plane of incidence. Used in (3).
a_o	Actual earth radius (6370 km = 3440 n mi).
A	A parameter used in tropospheric scatter calculations, from (44).
APODS	A program name (table 1).
ARD	Aviation Research and Development.
ATADU	A program name (table 1).
ATLAS	A program name (table 1).
ATOA	A program name (table 1).
A_{pe}	The reference plane ray bundle area (figure 1) associated with plane earth reflection in (2).

$A_r(q)$	Attenuation [dB] due to rain calculated via (34) for a fraction of time q.
$A_{rr}(q)$	Attenuation [dB] associated with rain rate and a fraction of time q (sec. 4.4, step 3).
A_s	Terrain attenuation [dB] from (55) that is associated with forward scatter.
A_{se}	The reference plane ray bundle area (figure 1) associated with plane earth reflection in (2).
A_Y	A conditional adjustment factor [dB] used to prevent available signal powers from exceeding levels expected for free-space propagation by unrealistic amounts, from (58).
A_{YI}	An initial of value of A_y dB, from (57),
$b_{1,2,3}$	Parameters with values from table 19 that are used in (26).
B	A parameter used in tropospheric scatter calculation, from (52).
c	The c-factor from tables 10 and 11 that is used in (31) and (32).
cm	Centimeters (10^{-2}m).
$c_{c,h,v}$	Phase (rad) of plane earth reflection coefficient relative to π for circular (18), horizontal (15), and vertical (14) polarization. The total phase lag associated with the reflection coefficient is ($\pi - c_{c,h,v}$) rad.
$c_{1,2}$	Parameters with values from table 19 that are used in (26).
C	A parameter used in tropospheric scatter calculations, from (53).
CCIR	International Radio Consultative Committee.
CRPL	Central Radio Propagation Laboratory.
d	Great circle distance between facility and aircraft. For line-of-sight paths, it is calculated as indicated in figure 2.

dB	Decibels, 10 log (dimensionless ratio of powers.
dBi	Antenna gain in decibels greater than isotropic.
dBW	Power in decibels greater than 1 watt.
dB-W/sq m	Power density in decibels greater than 1 watt per square meter.
deg	Degrees.
d_d	The d_o of IF-73 [17, (140)] that is used in (61) to calculate d_o for IF-77.
d_e	Effective distance [17, 177] that is used in (26).
d_{IL1}	An initial estimate of facility horizon distance, made via IF-73 [17, fig. 14].
$d_{Ls1,2}$	Smooth earth horizon distances determined via ray tracing (sec. 9.1).
$d_{L1,2}$	Horizon distances for facility and aircraft respectively. Values for d_{L1} are determined as in IF-73 [17, (38)].
$d_{Lo1,2}$	Smooth earth horizon distances determined via ray tracing (sec. 9.1) over a 9000 km (4860 n mi) earth.
d_o	The largest distance in the line-of-sight region at which diffraction effects associated with terrain are considered negligible, from (61).
$d_{\lambda 6}$	The largest distance at which a free-space value of basic transmission loss is obtained in a two ray model of reflection from a smooth earth with an effective reflection coefficient of -1. This occurs when the path length difference, Δr [17, (56)] is equal to $\lambda/6$.
D	Divergence factor, from (4).
DOC-BL	United States Department of Commerce, Boulder Laboratories
DOT	United States Department of Transportation.
DUDD	A program name (table 1).

DURATA	A program name (table 1).
D/U	Desired-to-undesired signal ratio [dB] available at the terminals of an ideal (loss less) receiving antenna.
D_s	Distance between radio horizons, from (64).
$D_{1,2}$	Distance shown in figure 2 [17, (51)].
eqn.	Equation.
exp(...)	Exponential; e.g., $\exp(2) = e^2$
EIRP	Equivalent Isotropically Radiated Power [dBW]
ESSA	Environmental Science Services Administration.
f	Frequency.
fss	Facility site surface (table 2).
ft	Feet.
ft-fss	Feet above facility site surface.
ft-msl	Feet above mean sea level.
$f_{\theta h}$	Elevation angle correction factor [17, (179)].
FAA	Federal Aviation Administration.
FTS	Federal Telecommunications System
$F_{d\sigma h}$	Reflection reduction factor associated with diffuse reflection and surface roughness [17, (194)].
F_r	Reflection reduction factor associated with ray lengths, from (7).
$F_{\sigma h}$	Specular reflection reduction factor associated with surface roughness [17, (66)].
g	Normalized voltage antenna gain used for the facility antenna in IF-73 [17, (67)].
g(g,f)	Frequency gain factor from (29) or (30).
$g_{D,R}$	Voltage gain [V/V] factors associated with direct and reflected rays, from (10) and (11).

$g_{D1,2}$	Voltage gain [V/V] of terminal antennas in the direction of the direct ray (figure 3) relative to main beam gain.
$g_{hD1,2}$	Voltage gain [V/V] similar to $g_{D1,2}$, but specifically for horizontal polarization.
$g_{hR1,2}$	Voltage gain [V/V] similar to $g_{R1,2}$, but specifically for horizontal polarization.
g_{Rv}	Gain factor for the reflected ray and vertical polarization, from (12).
g_{Rh}	Gain factor for the reflected ray and horizontal polarization, from (13).
$g_{R1,2}$	Voltage gain [V/V] of terminal antennas in the direction of the reflected ray (figure 3) relative to main beam gain.
$g_{vD1,2}$	Voltage gain [V/V] similar to $g_{D1,2}$, but specifically for vertical polarization.
$g_{vR1,2}$	Voltage gain [V/V] similar to $g_{R1,2}$ but specifically for vertical polarization.
GHz	Gigahertz (10^9 Hz)
GOES	Geostationary Operational Environmental Satellite.
$G_{R1,2}$	Gains [dB] $g_{R1,2}$ expressed in decibels, from (9).
G_T	Main beam gain [dBi] of transmitting antenna.
hr	Hours.
$h_{a1,2}$	Actual antenna elevations above reflecting surface elevation.
h_{cg}	Height of facility counterpoise above ground at the facility site.
$h_{e1,2}$	Effective antenna height above h_{rs}, from (68).
h_{fc}	Height of the facility antenna above its counterpoise.
h_{IL1}	Initial value of h_{L1}.

$h_{L1,2}$	Terminal horizon elevations.
h_{rs}	Elevation of reflecting surface above msl.
h_v	Common volume elevation above average terrain.
$h_{1,2}$	Antenna elevations above msl.
HDBK	Handbook.
HIPOD	A program name (table 1).
Hz	Hertz.
$H_{1/3}$	Significant wave height (table 5).
$H'_{1,2}$	Antenna elevations shown in figure 2 [17, (52)].
i	An index for specific transmission loss levels used in the distribution mixing process (sec. 4.1). It has values from 1 to M.
in	Inches.
IEEE	Institute of Electrical and Electronic Engineers.
ITS	Institute for Telecommunication Sciences.
IRE	Institute for Radio Engineers.
ITT	International Telephone and Telegraph.
IF-73	ITS-FAA-1973 propagation model.
IF-77	ITS-FAA-1977 propagation model.
j	$\sqrt{-1}$ or an index (1 to N) for specific transmission loss distributions used in the distribution mixing process (sec. 4.1).
JTAC	Joint Technical Advisory Committee.
km	Kilometer (10^3m).
ℓ	Total ray length, from (45).
log	Common (base 10) logarithm.
$\ell_{1,2}$	Terminal to common volume ray lengths.
LOBING	A program name (table 1).

L_{bf}	Basic transmission loss [dB] for free space [17, (15)].
L_{br}	Basic transmission loss [dB] calculated reference level [17, (17)].
m	Meters.
mhos	Unit of conductance or siemens.
min	Minutes.
mm	Millimeters (10^{-3}m).
msl	Mean sea level.
M	Number of transmission loss levels used in mixing distributions which is also the final value for the index i (sec. 4.1).
MIL	Military.
MHz	Megahertz (10^6 Hz).
n	A power used in the frequency scaling via (37).
n mi	Nautical miles.
nsec	Nanoseconds (10^{-9} sec).
N	Number of distributions to be mixed which is also the final value for the index j (sec. 4.1), or North latitude.
NBS	National Bureau of Standards.
NOAA	National Oceanic and Atmospheric Administration.
NTIA	National Telecommunications and Information Administration.
NTIS	National Technical Information Service.
N_o	Minimum monthly mean surface refractivity (N-units) referred to mean sea level [17, figure 3].
N_s	Minimum monthly surface refractivity in N-units [17, (18)].
N-unit	Units of refractivity [4, sec. 1.3] corresponding to 10^6 (refractive index -1).

P_{TR}	Total power [dBW] radiated, used in (77).
q	Dimensionless fraction of time used in time availability specification; e.g. Y_o (0.1) where $q = 0.1$ implies a time availability of 10 percent.
$q_{1,2}$	Parameters used in tropospheric scatter calculations from (51).
$q_{1,i,M}$	Time availabilities for mixed distributions that correspond to specific transmission loss levels, from (22).
$q_{11,ij,MN}$	Time availabilities for each transmission loss level (index i) of each transmission loss distribution (index j) involved in the distribution mixing process (sec. 4.1).
r	Ray length used in the calculation of free space loss, from (66).
rad	Radians.
rms	Root mean square.
r_{BH}	Ray length for beyond-the-horizon paths, from (65).
$r_{eo,s,w}$	Effective ray lengths (sec. 4.4) for attenuation associated with oxygen absorption, (r_{eo}), rain storm attenuation (r_{es}), and water vapor absorption (r_{ew}).
r_o	Direct Ray length shown in figure 2 [17, (54)].
$r_{L1,2}$	Antenna to horizon ray lengths for airless earth, from (63).
r_s	In-storm ray length used in rain attenuation calculation, from (33).
r_{WH}	Within-the-horizon ray length for airless earth, from (62).
$r_{1,2}$	Segments of reflected ray path shown in figure 2 and components of r_{12}.
r_{12}	Reflected ray path length as shown in figure 2 [17, (55)].

R	Magnitude of complex plane earth reflection coefficient.
RTA-2	A TACAN antenna type.
$R_{c,h,v}$	Magnitudes of complex plane earth reflection coefficients for circular, horizontal, and vertical polarization.
R_r	A parameter used in the calculation of the divergence factor, from (5).
s	Modules of asymmetry used in tropospheric scatter calculations, from (43).
sec	Seconds.
sq m	Square meters.
s mi	Statute miles.
SHF	Super High Frequency (3 to 30 GHz).
Sin^{-1}	Inverse sine with principal value.
SRVLUM	A program name (table 1).
S_e	Scattering efficiency term [dB] used in tropospheric scatter calculations, from (42).
S_v	Scattering volume term [dB] of tropospheric scatter calculations, from (54).
T	Relaxation time [µs] used in the calculation of surface constants for water (table 6).
TACAN	TACtical Air Navigation, an air navigation aid used to provide aircraft with distance and bearing information.
TWIRL	A program name (table 1).
$T_{eo,s,w}$	Height or layer thickness (sec. 4.4) used in attenuation calculations for oxygen absorption (T_{eo}), rain storm attenuation (T_{es}), or water vapor absorption (T_{ew}).
UHF	Ultra-High Frequency (300 to 3000 MHz).
V	Volts.

$V_c(q)$	Variability for specific climate or time block, from (23).
$V_{1,i,M}$	Variability levels ($V_1,...V_i,...V_M$) used in mixing process (sec. 4.1).
W	Watts.
$W_{1,j,N}$	Weighting factors ($W_1,...W_j,...W_N$) used in mixing process (sec. 4.1).
$Y(q)$	Variability (dB greater than median) of hourly median received power about its median, from (27), (28), (31) and (32).
Y_c	A complex parameter used in the calculation of the plane earth reflection coefficient, from (16).
$Y_e(q)$	Effective variability (dB greater than median) of hourly median received power about its median, from (59) and (60).
$Y_{eI}(q)$	Initial value $Y_e(q)$ from (56).
$Y_I(q)$	Variability [dB] associated with ionospheric scintillation (figure 7).
$Y_{Ic}(q)$	$Y_I(q)$ for a particular distribution to be used in the mixing process to obtain resultant $Y_I(q)$, from (25).
$Y_r(q)$	Variability (dB greater than median) associated with rain attenuation, from (35).
Y_T	A parameter from IF-73 [17, (182)].
$Y_o(0.1)$	A reference variability level used to calculate Y(0.1), from (26).
$Y_o(0.9)$	A reference variability level used to calculate Y(0.9), from (26).
$Y_{136}(q)$	Variability associated with ionospheric scintillation at 136 MHz.
$Y_\pi(q)$	Variability (dB greater than median) associated with multipath [17, p. 38].
$Y_\Sigma(q)$	Total variability (dB greater than median), from (36).

α	An angle shown in figure 2 [17, (53)].
γ	A parameter in tropospheric scatter calculations, from (40).
Δh	Terrain parameter used to characterize terrain [17, sec. A.4.1; 26, sec. 2.2].
$\Delta h_{a1,2}$	Adjusted effective altitude correction factors, from (70).
$\Delta h_{e1,2}$	Effective altitude correction factors, from (69).
Δr	Path length difference for rays shown in figure 2 [17, (56)].
ε	Dielectric constant from table 6 or calculated for water using (20).
ε_c	Complex dielectric constant, from (17).
ε_o	Dielectric constant representing the sum of electronic and atomic polarizations. For water, $\varepsilon_o = 4.9$.
ε_s	Static dielectric constant (table 6).
$\varepsilon_{1,2}$	Parameters used in tropospheric scatter calculations, from (39) and (41).
η	A parameter used in tropospheric scatter calculations, from (46).
Θ	Scattering angle used in tropospheric scatter calculations. It is the angle between transmitter horizon to common volume ray and the common volume to receiver horizon ray as both leave their crossover point.
Θ_{e1}	Elevation angle of horizon from the facility, from (74).
Θ_{e2}	Elevation angle of horizon from the aircraft [17, (39)].
Θ_{FL}	Latitude of earth facility for (38).
$\Theta_{g1,2}$	Elevation angles of the ground reflected rays at the terminal antennas, from (80).
$\Theta_{h1,2}$	Parameter used to calculate $\Theta_{H1,2}$ from (78).

$\Theta_{H1,2}$	Direct ray elevation angles at the terminal antennas, from (79).
Θ_{Iel}	Initial estimate of Θ_{el}; i.e., Θ_{el} as calculated in IF-73 [17, figure 14].
Θ_L	A ray tracing take-off angle at the facility horizon, from (76).
$\Theta_{L1,2}$	Horizon elevation angle adjustment terms, from (81).
$\Theta_{LE1,2}$	Horizon elevation angles as determined with effective earth radius model, for (81).
$\Theta_{LR1,2}$	Horizon elevation angles as determined with ray tracing, for (81).
$\Theta_{s1,2}$	Central angles below the smooth earth terminal to horizon distances for the effective earth model, from (67).
Θ_o	Angle defined in figure 2.
$\Theta_{1,2}$	Angles shown in figure 2.
κ	Wave number, from (49).
λ	Wavelength.
μs	Microseconds (10^{-6} sec).
$\rho_{1,2}$	Parameters used in tropospheric scatter calculations, from (50).
σ	Surface conductivity [mho/m] from (21) or table 6.
σ_h	Root-mean-square deviation of surface excursions within the limits of the first Fresnel zone in the dominant reflecting plane [17, (65)], from table 5 or (1).
σ_i	Ionic conductivity [mho/m], from table 6.
$\chi_{1,2}$	Parameters used in tropospheric scatter calculations, from (47) and (48).
ψ	Grazing angle shown in figures 2 and 3.
ψ_B	Grazing angle associated with the pseudo Brewster angle, from (19).

°C	Degrees celsius.
°F	Degrees fahrenheit.
$(\ldots)^\circ$	Degrees; e.g. 12°.
$\ldots]_c$	Expression evaluated for specific conditions such as climate or time block in (23).
$\ldots]_L$	Expression evaluated for radio horizon conditions.
$\lvert\ldots\rvert$	Magnitude of expression; e.g., $\lvert 1-j\rvert = \sqrt{2}$

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